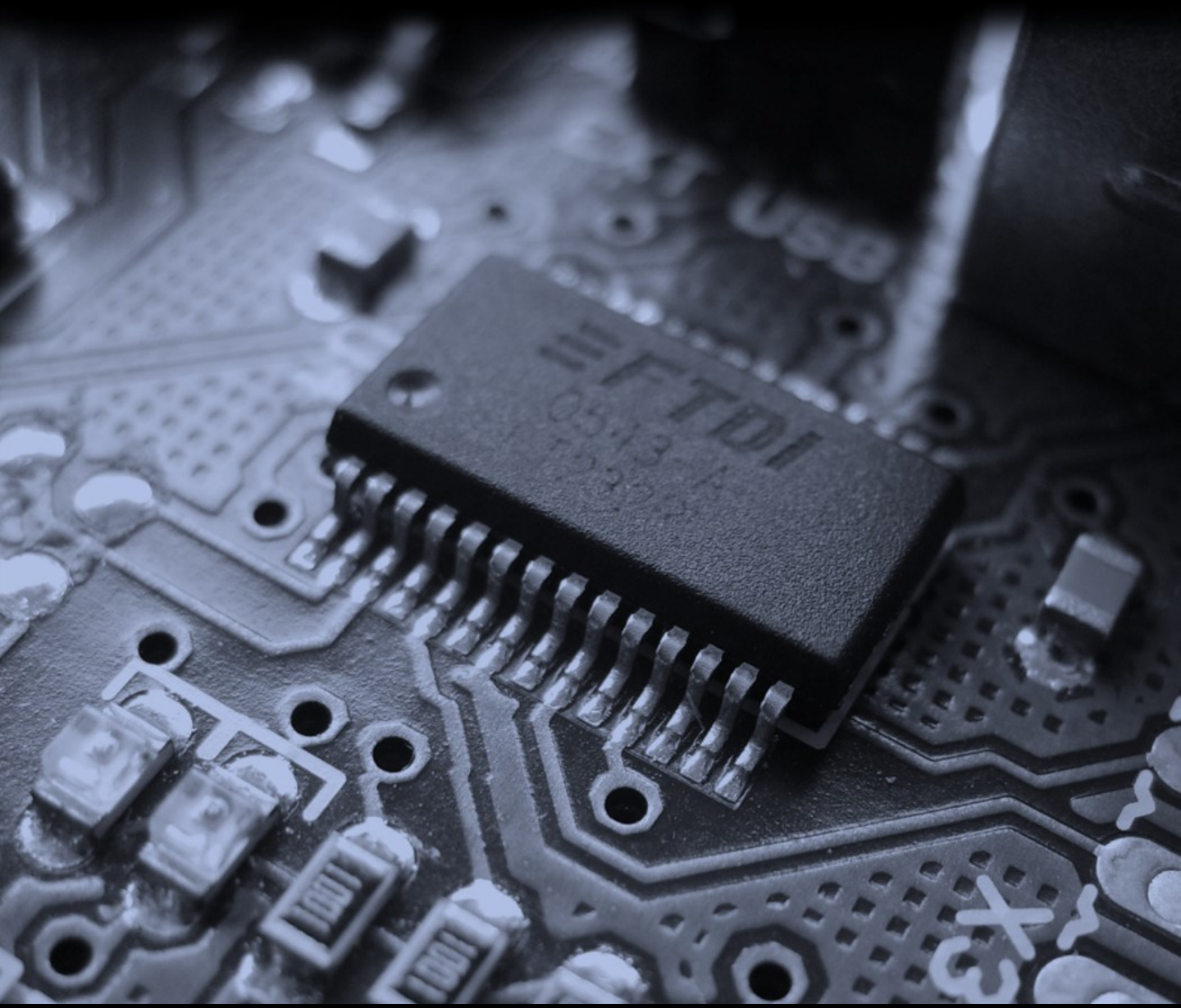
AUSTRALIAN JOURNAL OF ENGINEERING AND TECHNOLOGY RESEARCH

Volume 1, Issue 1 - 2016



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INTRODUCTION

(Muhammad Nabeel Musharraf)

We are highly excited to present the first issue of **Australian Journal of Engineering and Technology Research.** It has been my pleasure to serve as the chief editor of this journal and contribute to its launch.

Following is a brief overview of our journal, its purpose and current issue.

PURPOSE:

AJETR is a multi-disciplinary and open-access publication launched with an aim to encourage and facilitate the original research with a particular focus on developing countries. Accordingly, all publication fees are waived off for students from 28 different universities from these countries.

Our scope covers a broad range of engineering and technology related disciplines. Research papers, book reviews, thesis and other scholarly works can be submitted for review throughout the year. Each year, **AJETR** has planned to launch two issues.

We aim to go a step ahead of other journals in terms of our commitment to nurturing the future researchers. In order to further this aim, we will be more than pleased to guide, assist and train young researchers and help them pave their way into an exciting research career. We are also very keen to form partnerships with universities in order to provide them useful research support and train their young researchers.

OVERVIEW OF CURRENT ISSUE:

This issue contains some very exciting research papers.

The first paper, *Design of Maintenance Management System for Manufacturing Organizations*, presents a design framework for MIS that can be implemented in a number of different manufacturing industries considering its generic features and holistic nature. The details cover the stakeholder mapping, database design considerations, data handling, interfacing and other relevant aspects. The paper contains ample diagrams, figures and illustrations.

The second paper, *Design of Mechatronics Engineering Associate Degree Programs – An Overview*, summarizes researcher's experience of implementing Mechatronics Engineering program at a

middle-eastern university. Course outlines provided in this paper can be useful for institutions looking forward to offer similar programs.

The third paper, *Surface Water Treatment is a Big Challenge for North Sindh - A Case Study Of 18mgd wtp Numaishgah, Sukkur*, presents a case study of water treatment at a facility in Pakistan. Article provides useful insights and recommendations regarding the water quality improvement.

The fourth article, *Fluid Flow in an Asymmetric Channel of Variable Cross-Section with Slip Condition at the Wall*, provides detailed mathematical calculations with regards to the fluid flow under certain factors and conditions. These calculations are very useful for a range of disciplines and contribute to furthering the engineering knowledge on the subject.

The fifth article, *Laboratory Investigation of Cement Permeability by Using Different Chemicals*, assesses the permeability of cement with different compositions and constituents. This research is highly useful in well design and other relevant applications.

I would like to extend my gratitude to all researchers, reviewers and others who supported Australian Research Journals in launching this research journal and presenting the current issue. We hope it comes out as a highly beneficial endeavour for the whole engineering and technology research community.

Yours Sincerely,

Muhammad Nabeel Musharraf

July 5, 2016

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MS (Embedded Systems Informatics) from University of Trento
B. E. Computer Systems (Honours) from NUST, Pakistan (Gold Medallist)

NUMBERING PROTOCOL:

The following protocol is deployed for numbering the journal issues:

1. Volume:

A new volume is commenced each calendar year (For example, Vol1 contains article entries for 2016, Vol2 will contain entries for 2017 etc.)

2. Issue:

Two issues shall be released each year with the basis of classification as follows:

- 1st Issue of the calendar year: Issue 1
- 2nd Issue of the year: Issue 2

Number of months included in each issue: 6

Examples:

- Australian Journal of Engineering and Technology Research, Vol. 1, Issue 1 (Jan-Jun 2016)
- Australian Journal of Engineering and Technology Research, Vol. 1, Issue 2 (Jul-Dec 2016)
- Australian Journal of Engineering and Technology Research, Vol. 2, Issue 1 (Jan-Jun 2017)

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AUSTRALIAN JOURNAL OF ENGINEERING AND TECHNOLOGY RESEARCH (AJETR)
Vol.1, Issue 1 - 2016

DESIGN OF MAINTENANCE MANAGEMENT SYSTEM FOR MANUFACTURING ORGANIZATIONS

Muhammad Nabeel Musharraf

ABSTRACT:

Maintenance is an extremely important function that ensures the availability and reliability of production systems. In order for maintenance to function effectively, an effective information management system is essential. However, we see that many commonly found maintenance management systems lack important functions. In this paper, we have presented the development process for a medium-sized maintenance information management system and reviewed various phases of its design, development, and testing including relevant functions and processes. The proposed model can be customized to adjust the scope and to be contextualized according to specific organizational needs.

Introduction:

Information systems have revolutionized the way industrial operations are managed nowadays (Fountas et al., 2015). Long gone are the days when the bill of material (BOM) for equipment used to be searched from hand-written or dot-matrix printers. It is now available in a single click through management information systems designed for various departments within and between the companies and organizations. Considering a vast number of equipment, spare parts, maintenance procedures and techniques used in the field of maintenance, the importance of MIS is unquestionable. In this paper, we will propose a design for an effective maintenance information management system.

Objective:

This paper aims to explain the key aspects related to design including:

- Design basis,
- Use cases,
- Entity relationship diagrams, and
- Test cases.

Project Significance:

Modern maintenance management is not to repair broken equipment rapidly. Modern maintenance management is to keep the equipment running at high capacity and produce quality products at the lowest cost possible. Maintenance information management systems play a huge role in this.

This project can be used as a framework for the design of maintenance management system in terms of breaking down the complex maintenance aspects to manageable components which can be further built upon and developed.

The proposed design ensures departmental integrations with and within Maintenance function and accordingly carries a huge potential for maintenance management optimization through this MIS.

Actors Catalogue:

An actor may perform many different functions or play many different roles in a system. Also, there may be many actors in the system.

For the purpose of this project, key actors considered in this system will be the following:

- Supply chain team
- Maintenance team
- Management
- Engineering Spares Team
- Production Team

Functional Requirements:

System requirements are a list of necessary functions, capabilities, or characteristics related to the system being developed and the plans for creating it. There are several types of requirements that may be defined during the process that comes together to focus and prioritize the project plan. System requirements can be of various types and 'functional requirements' is one of its these different types. Functional Requirements provide details of how a product should behave and specify what is needed for development ("Website Requirements," 2013).

Following will be the functional requirements for proposed design:

- Ability to store Master Data (including names and numbers of machines, spare parts BOM, maintenance BOM, Type of maintenance, budgets etc)
- Ability to produce and store 12 months (rolling) maintenance plan based on master data and functional inputs, retrievable by relevant functions
- Ability to store breakdown/ failure records and prepare necessary statistics in order to facilitate decision-making
- Ability to incorporate special maintenance requests under exceptional circumstances
- Ability to generate overall maintenance and machine-wise costs
- Ability to generate reports
- Ability to generate spares ordering schedule

Use Cases:

A use case is a written description of how users will perform tasks on your system. It outlines, from a user's point of view, a system's behavior as it responds to a request. Each use case is represented as a sequence of simple steps, beginning with a user's goal and ending when that goal is fulfilled ("Use Cases," 2013). US government's 'usability' mentions: "Use cases add value because they help explain how the system should behave and in the process, they also help brainstorm what could go wrong. They provide a list of goals and this list can be used to establish the cost and complexity of the system. Project teams can then negotiate which functions become requirements and are built ("Use Cases," 2013).

Following is the broad overall use-case diagram for the project showing various interactions in line with the functional requirements:

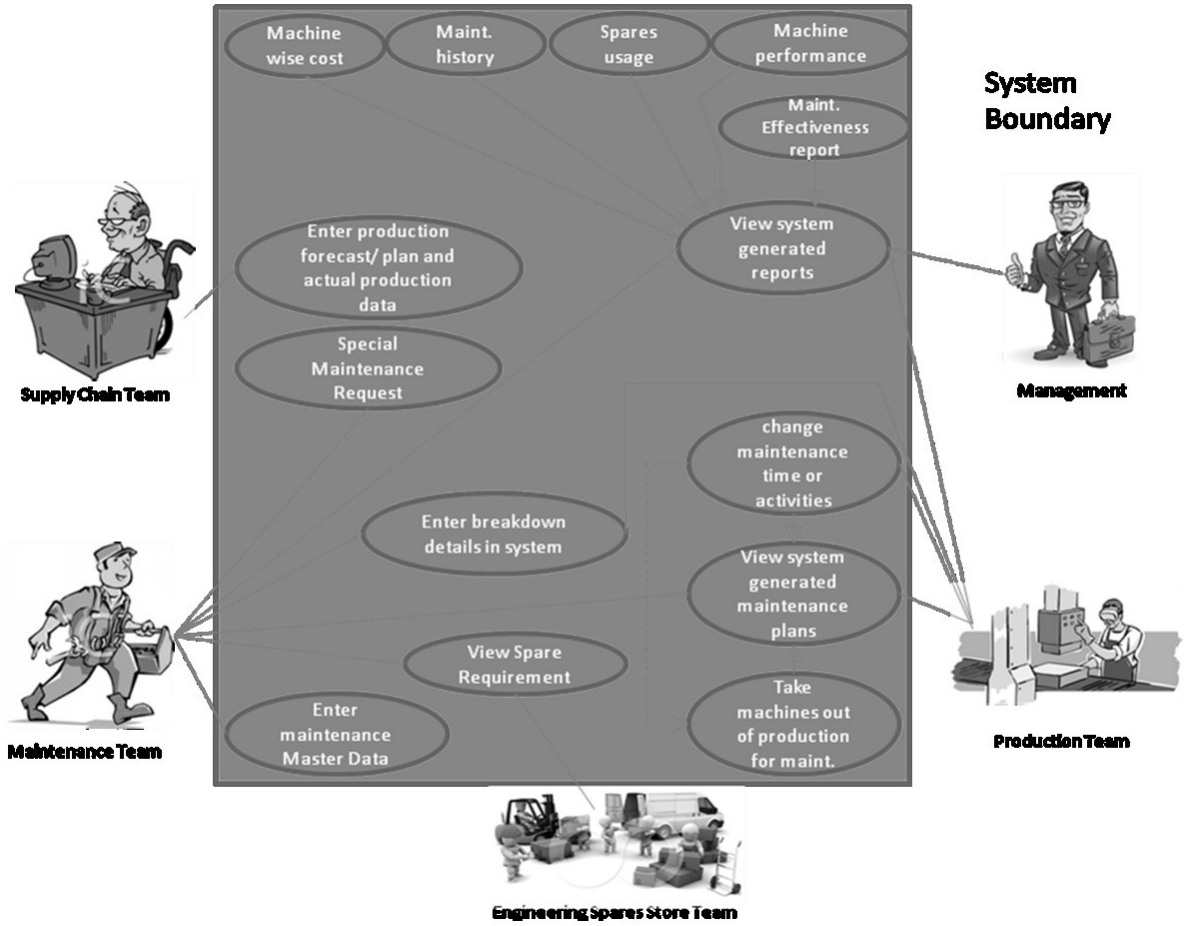

Figure 1: System Use Case

This broad use-case diagram has been divided into further individual cases to provide a better overview of relationships and interaction with systems.

Maintenance Team enters master-data in the system. This master-data is used for managing spares with regards to their life, replacement schedules, and maintenance plans:

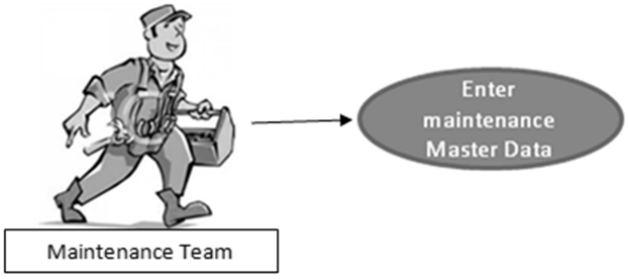

Figure 2: Entry of Master-data

Supply chain team enters production forecast, production plan, and actual performance. Maintenance of equipment would be dependent on these forecasts. Also, there would be some fixed life spares which are also classified as 'fast-movers'. Their availability in stores would be dependent on correct entry of production data. System would be able to generate the purchase orders for suppliers based on production forecast and actual performance in accordance with re-order levels:

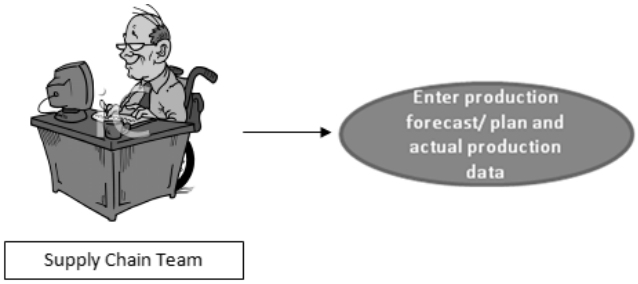

Figure 3: Entry of production data

Engineering team enters the spares requirement for various equipment in the system. Maintenance team extracts the requirements from system in case of planned maintenance activities and any specific spares required during pre-defined breakdown repairs:

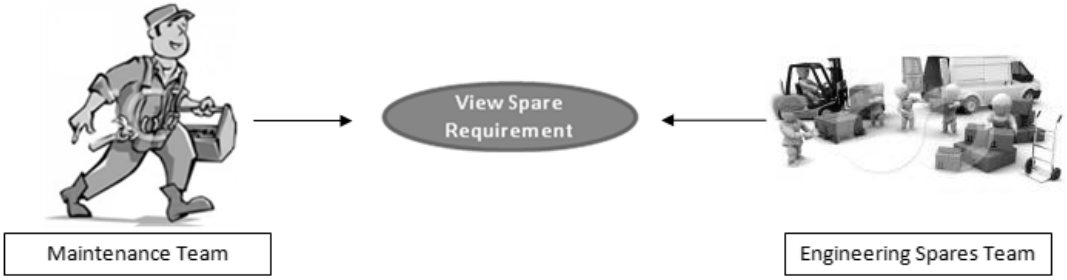

Figure 4: Entry of spare parts requirements

Maintenance teams and productions teams can raise work orders to any special maintenance requirement identified during operation or maintenance. It is important to record these events so that spares can be issued against particular equipment. This would help managements and other relevant stakeholders view how each piece of equipment is performing and if there are any trends. This information can have also other uses e.g. analysis of usage for a particular type of spare. System reports can show a rise in spare requirement on an equipment or across the board which can then be followed up by actions.

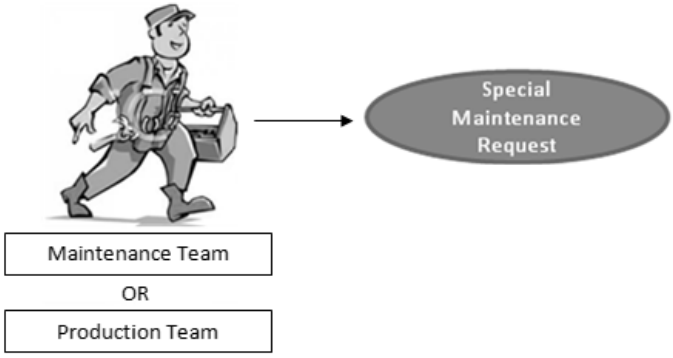

Figure 5: Entry of special maintenance requests

Production and maintenance teams need to be able to input the breakdowns. Its reasons justifications are the same as given in above use-case.

Figure 6: Entry of breakdown details

Equipment has to be maintained in line with relevant manufacturer guideline, organizational procedures, and other aspects. These plans should not be based on memory and should be fed in the system for an automatic generation at given timeframes. Maintenance and production teams should be able to view these plans so that they can plan their operations, rosters and other relevant aspects.

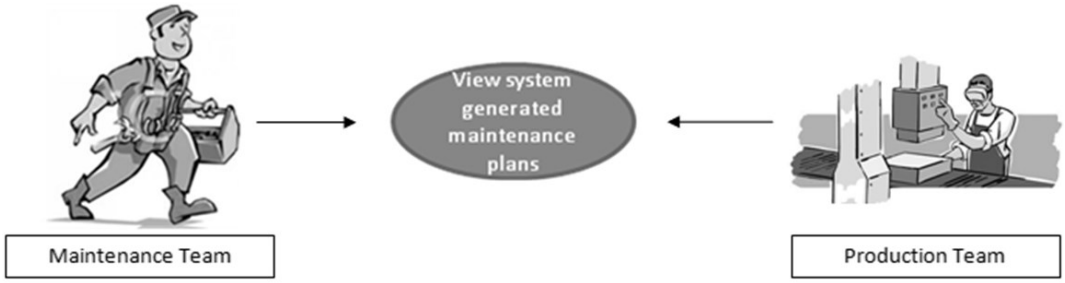

Figure 7: Entry of system generated maintenance plans

Maintenance plans may need to be changed due to factors such as unavailability of spares, results of predictive maintenance, operational and maintenance priorities etc. This capability should accordingly be there is the system. Also, it is important that machines are taken out of production in the system, irrespective if the maintenance is planned or unplanned, so that system can assess the capability to meet production demands. If demands cannot be met because of some unplanned maintenance work, the system can report this to relevant stakeholders.

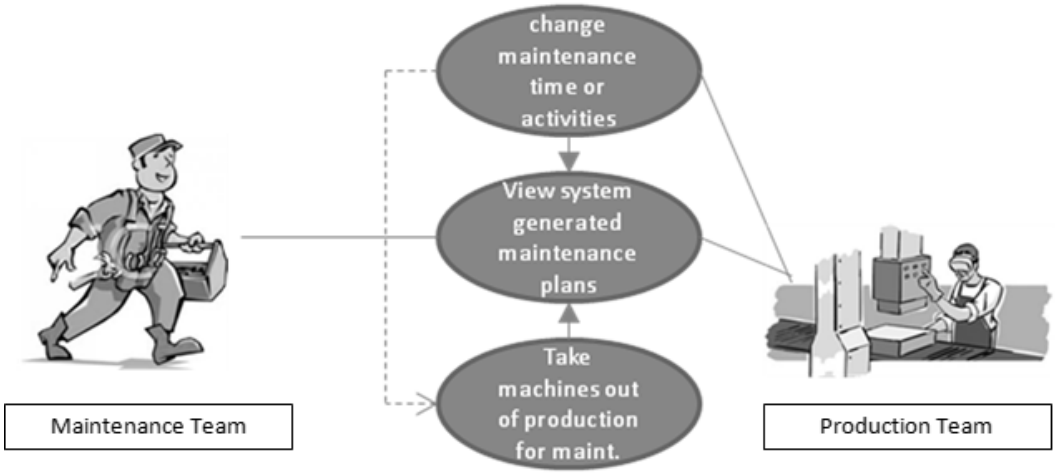

Figure 8: Operational activities during maintenance

Based on this information system can generate a number of reports for stakeholders.

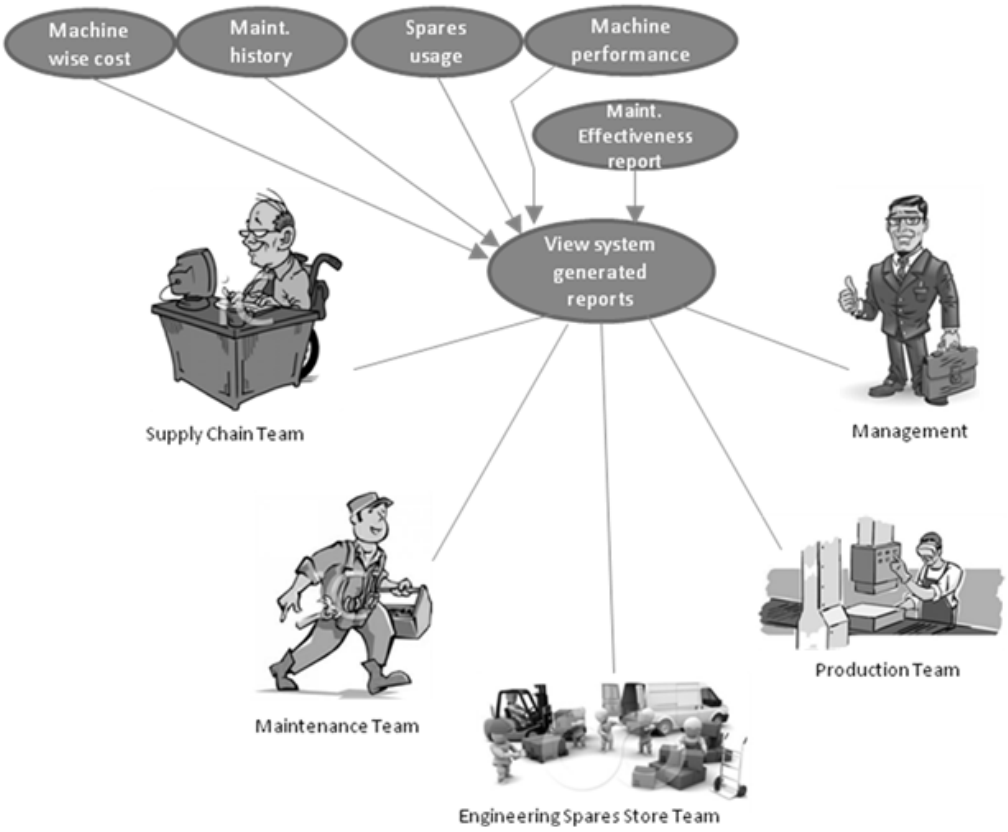

Figure 9: System generated reports

ARCHITECTURAL DESIGN:

System's architectural design is explained in figure 10.

The architecture consists of three layers which represent functions and relevant HMI of the system based on above mentioned use-cases.

Presentation layer:

The presentation layer provides the application's user interface (Microsoft Corporation, 2015). This layer in our proposed system architecture provides facility to various stakeholders to interact with the system as shown in figure 10 which also highlights relevant screens that are required to be built in the HMI (human machine interface).

Logic Layer:

In this layer, aspects which are required to be covered in the programming phase with regards to system functional requirements are explained.

Data Layer:

The data layer provides access to external systems such as databases. Figure 10 shows relevant information which is required to be stored.

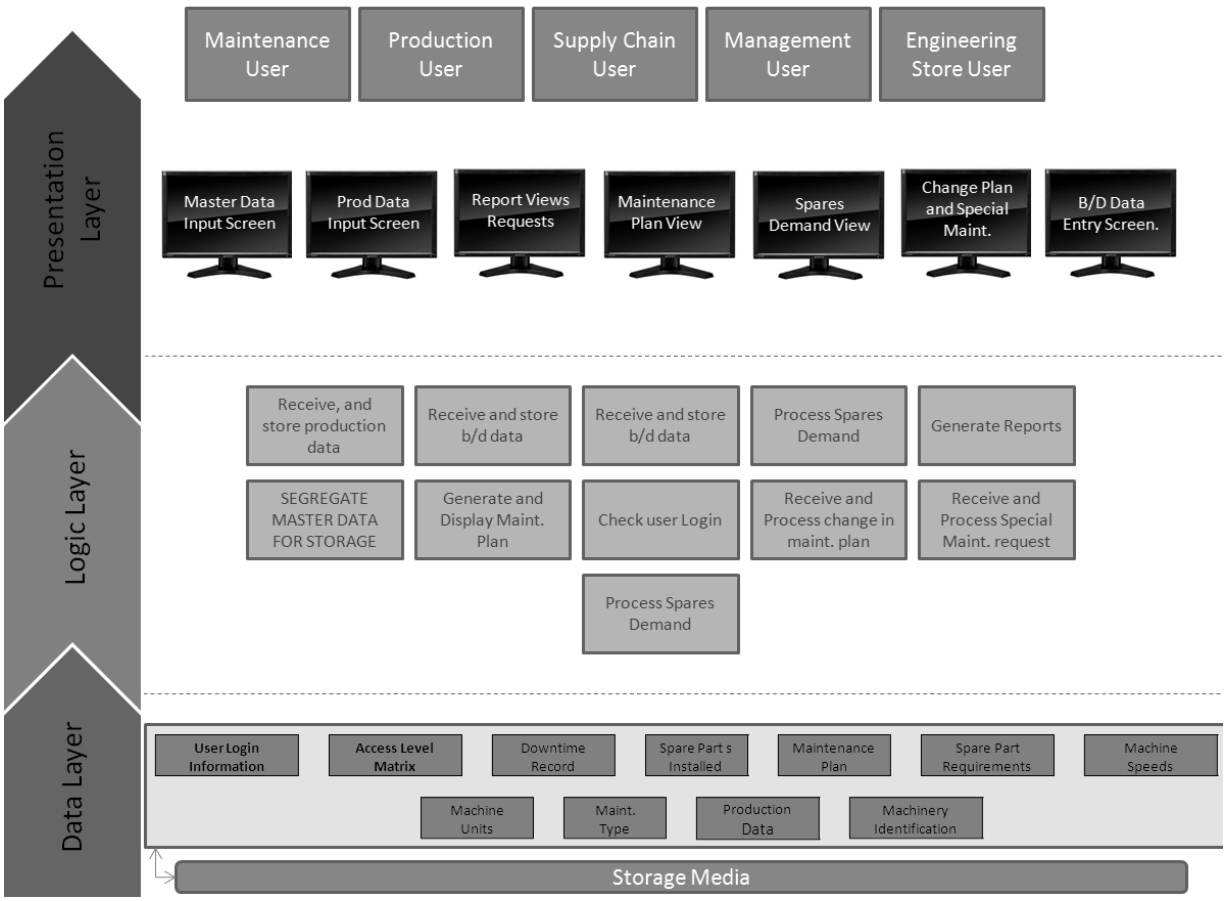

Figure 10: System Architecture

Hardware architecture is defined in three tiers:

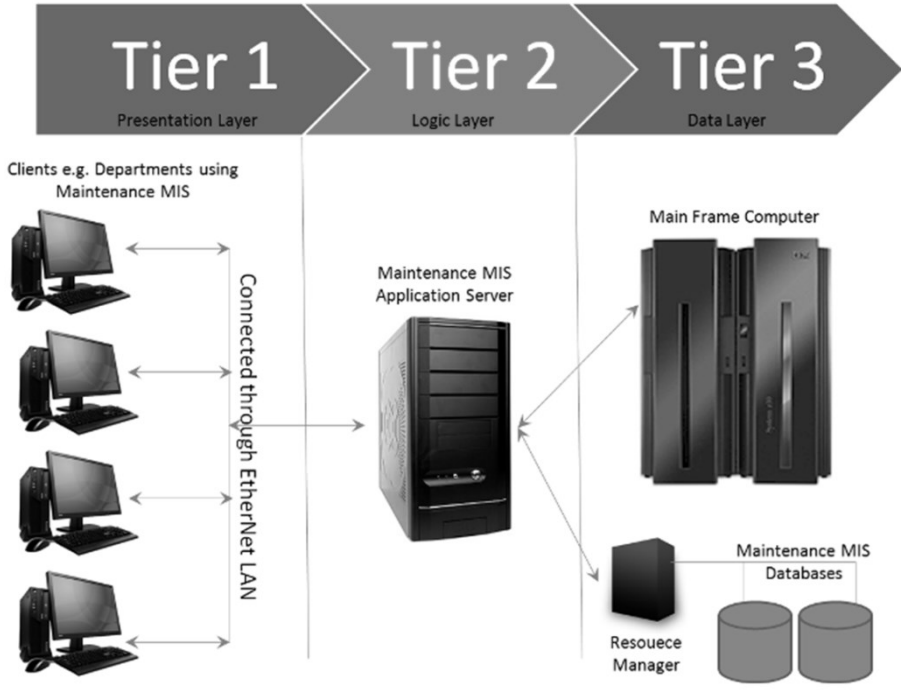

Figure 11: Hardware Architecture

PROJECT SCOPE:

Based on use-cases explained in previous sections, following is a description of proposed systems project scope and relevant interactions with various stakeholders.

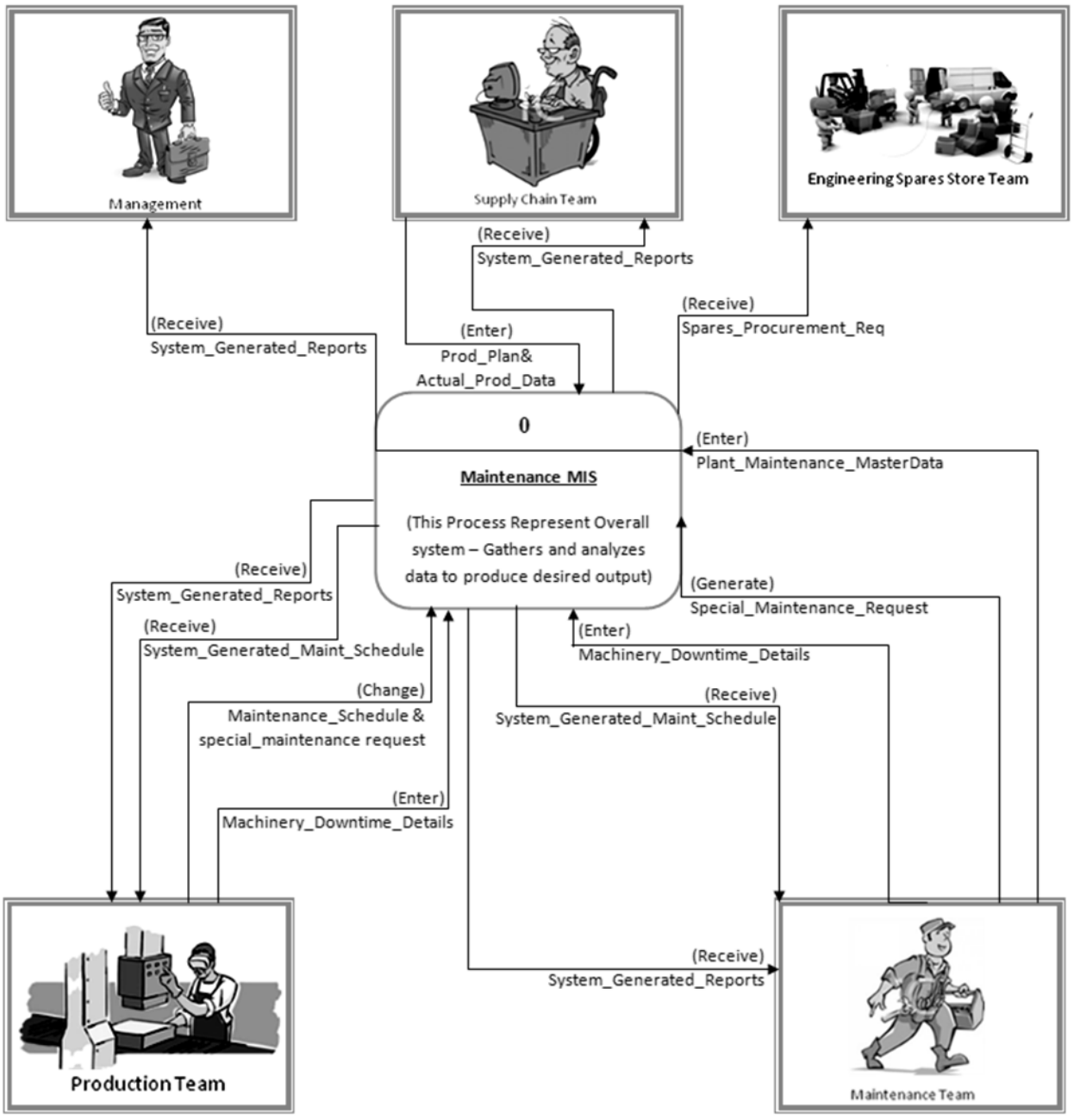

Figure 12: Project Scope

Above figure shows level zero data-flow diagram which considers the whole system as a single entity, like a black-box without any attention being paid to what is happening in that box.

Further details data-flow diagrams explore the inside of this box and explain the internal functionality.

DETAILED DATA-FLOW DIAGRAM:

Following is the detailed dataflow diagram for the system showing internal processes.

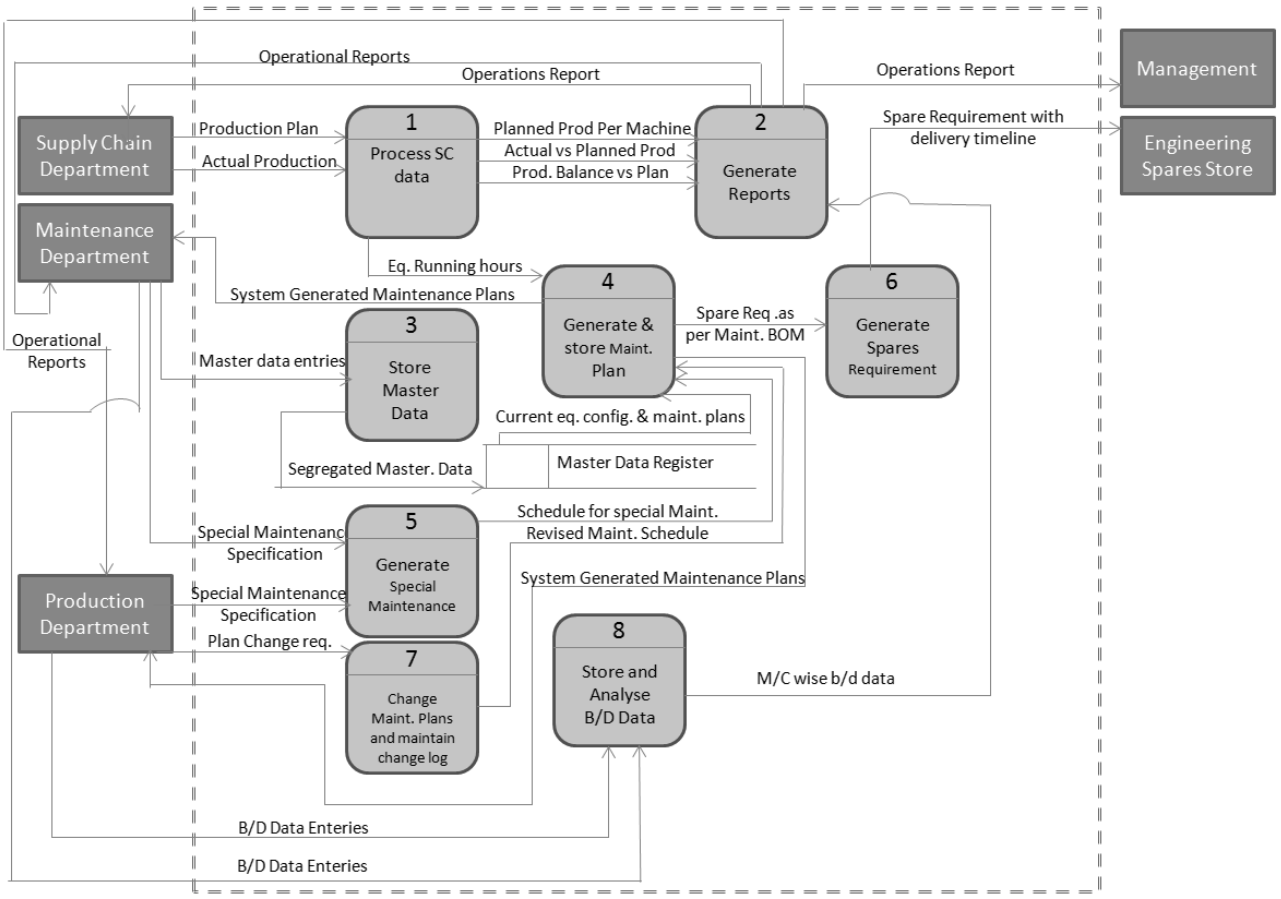

Figure 13: System Dataflow diagram

SEQUENCE DIAGRAMS:

A Sequence diagram is an interaction diagram that shows how processes operate with one another and in what order. It is a construct of a Message Sequence Chart. A sequence diagram shows object interactions arranged in time sequence. It depicts the objects and classes involved in the scenario and the sequence of messages exchanged between the objects needed to carry out the functionality of the scenario. Sequence diagrams are typically associated with use case realizations in the Logical View of the system under development. Sequence diagrams are sometimes called event diagrams or event scenarios.

A sequence diagram shows, as parallel vertical lines (lifelines), different processes or objects that live simultaneously, and, as horizontal arrows, the messages exchanged between them, in the order in which they occur. This allows the specification of simple runtime scenarios in a graphical manner.

With regards to the current project, we have prepared detailed sequence diagrams explaining various internal functions, data movement, storage and stakeholders for this system.

Sequence diagrams have been presented below.

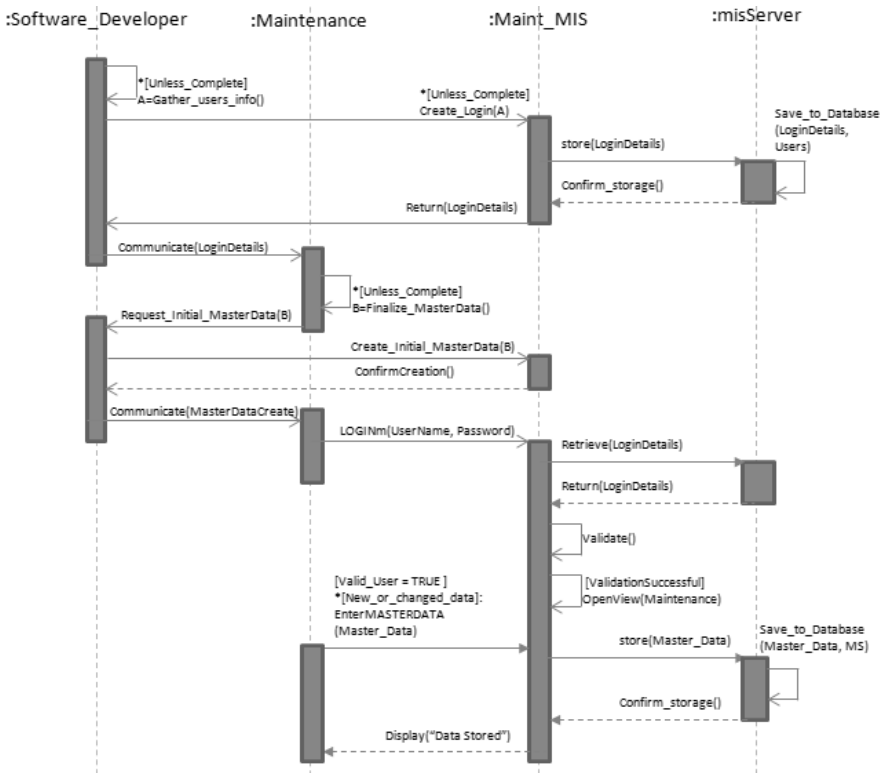

Figure 14. Sequence diagram 1

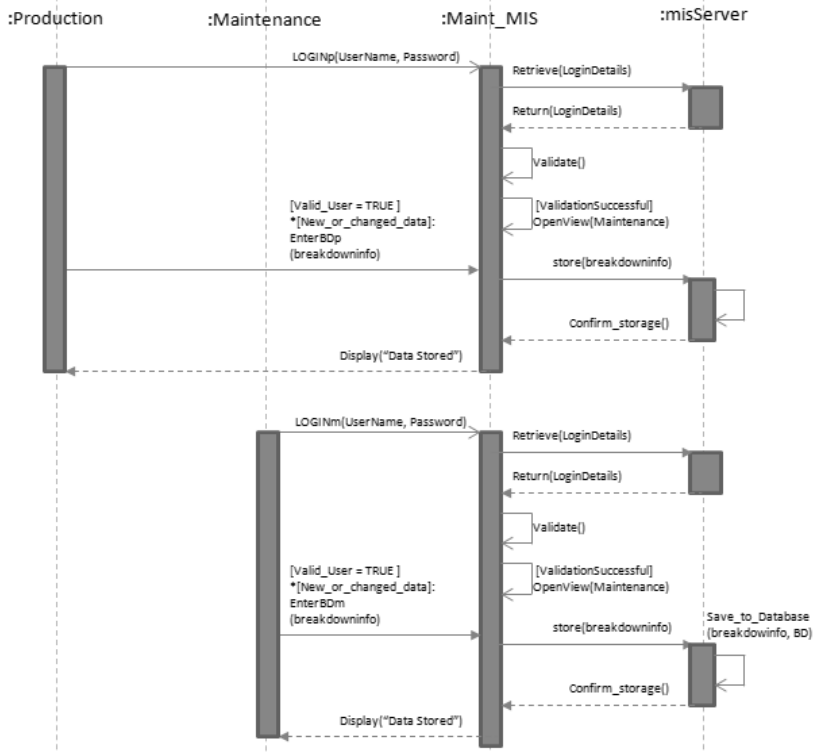

Figure 15. Sequence diagram 2

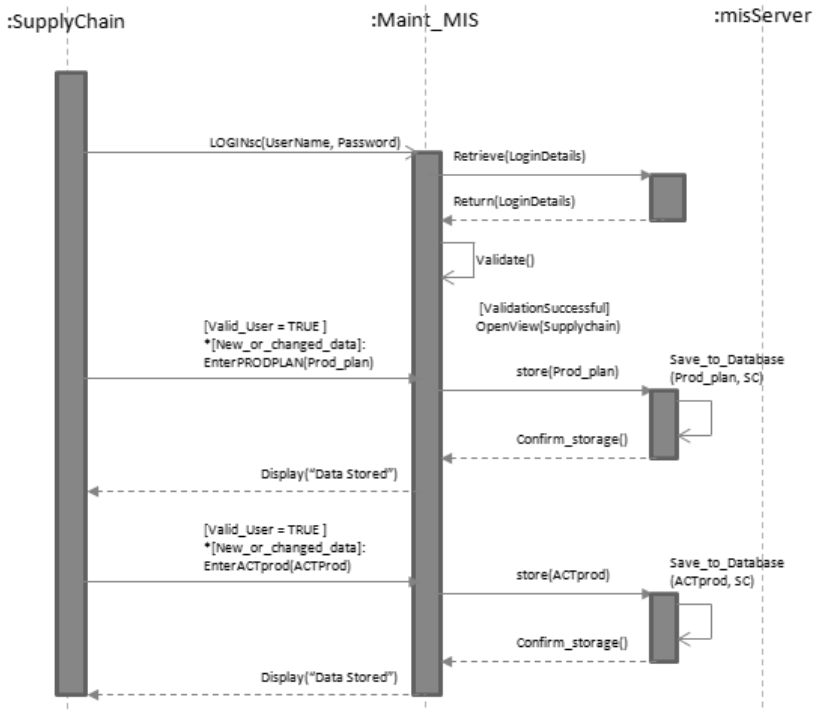

Figure 16. Sequence diagram 3

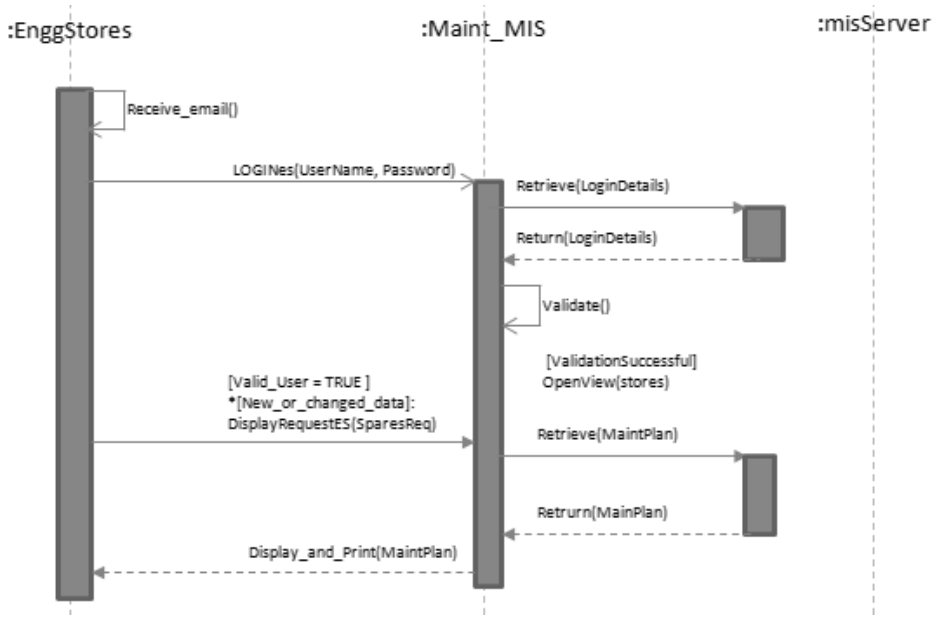

Figure 17. Sequence diagram 4

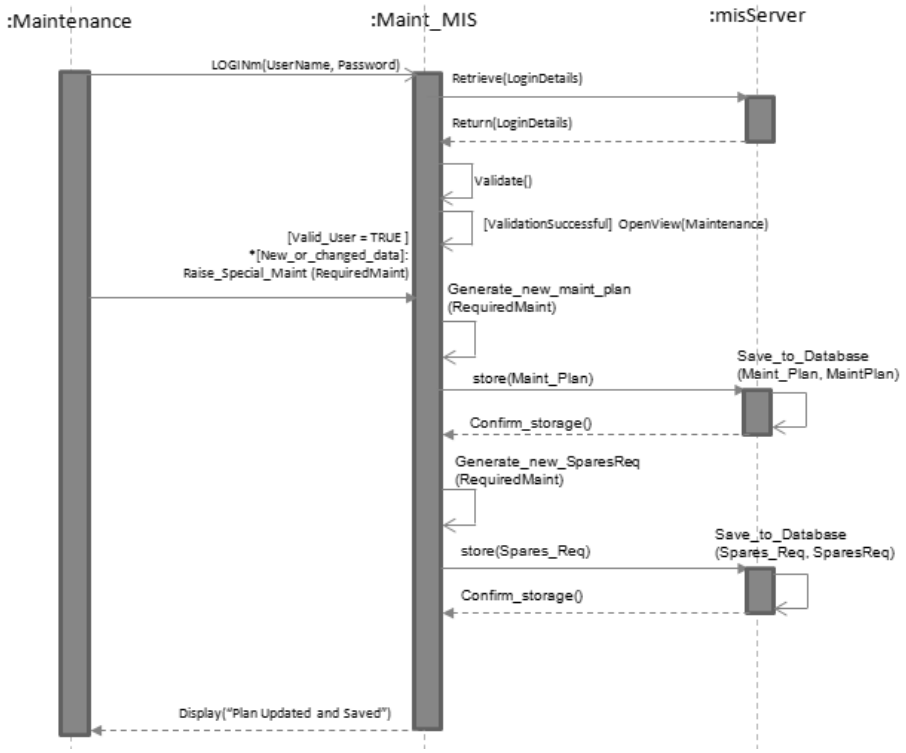

Figure 18. Sequence diagram 5

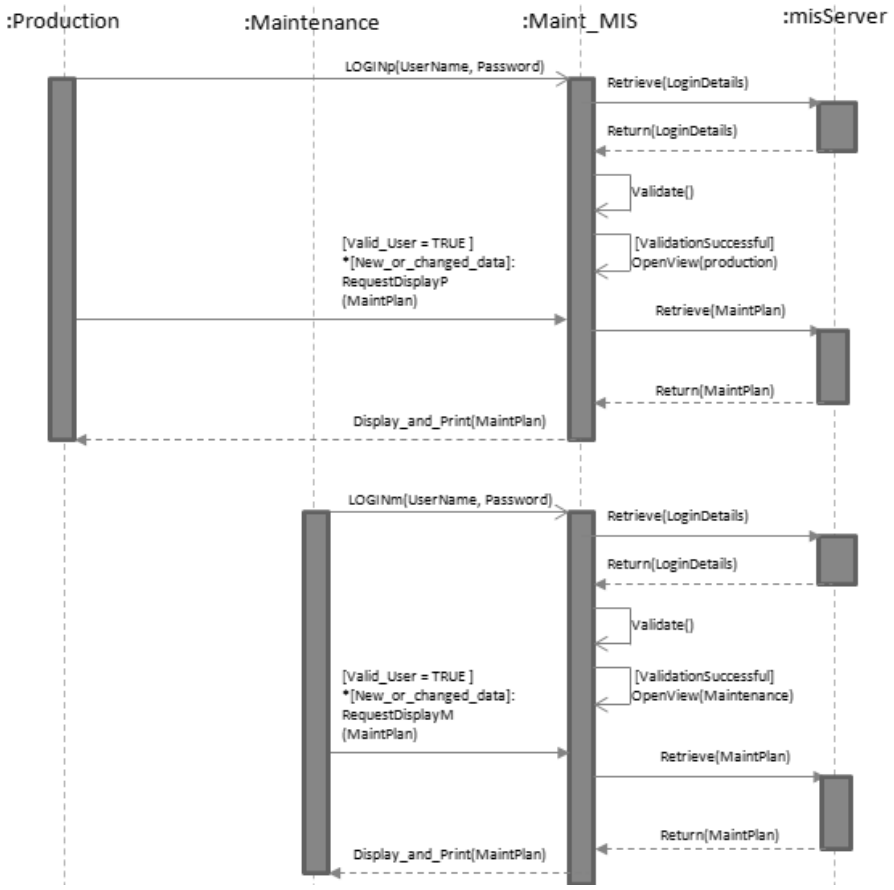

Figure 19. Sequence diagram 6

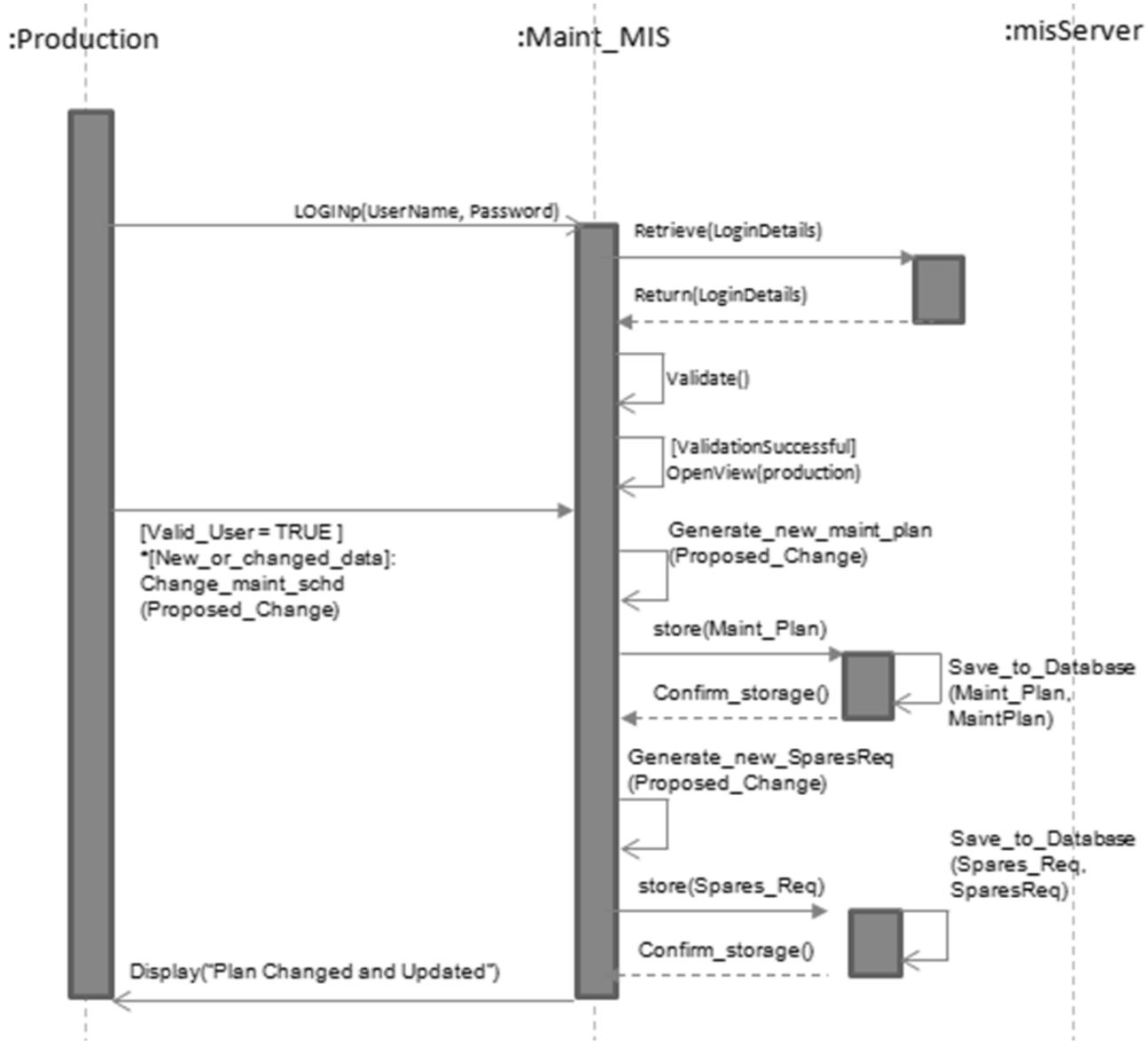

Figure 20. Sequence diagram 7

Reporting is one of the major functions of MIS. Accordingly, it involves a lot of relevant processes and sharing of information from one element of the system and organization to the other. Relative to other types of specialized information systems, an MIS is used by mid-level management to support ongoing operations. The emphasis is on making routine decisions. MIS relies mostly on internal sources of information (Zandbergen, 2015).

One of the important roles of an MIS is to provide the right information to the right person in the right format at the right time. Information is collected within the organization on an ongoing basis and an MIS processes this information, so managers get the summarized reports. Information is typically in the form of reports on a daily or weekly basis.

In our case, the next sequence diagram explains the reporting processes and how do different stakeholders deal with it.

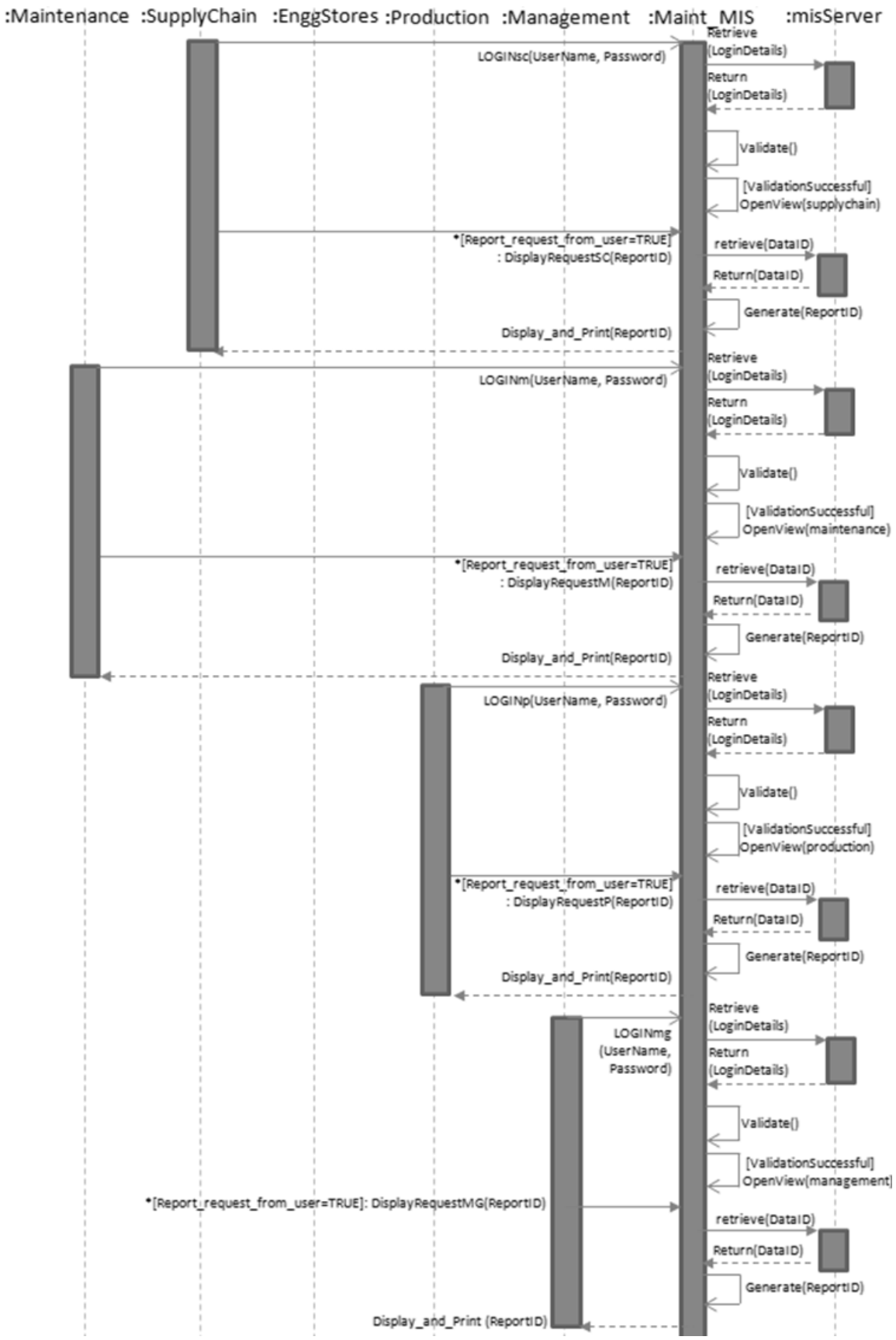

Figure 21: Sequence diagram for reporting

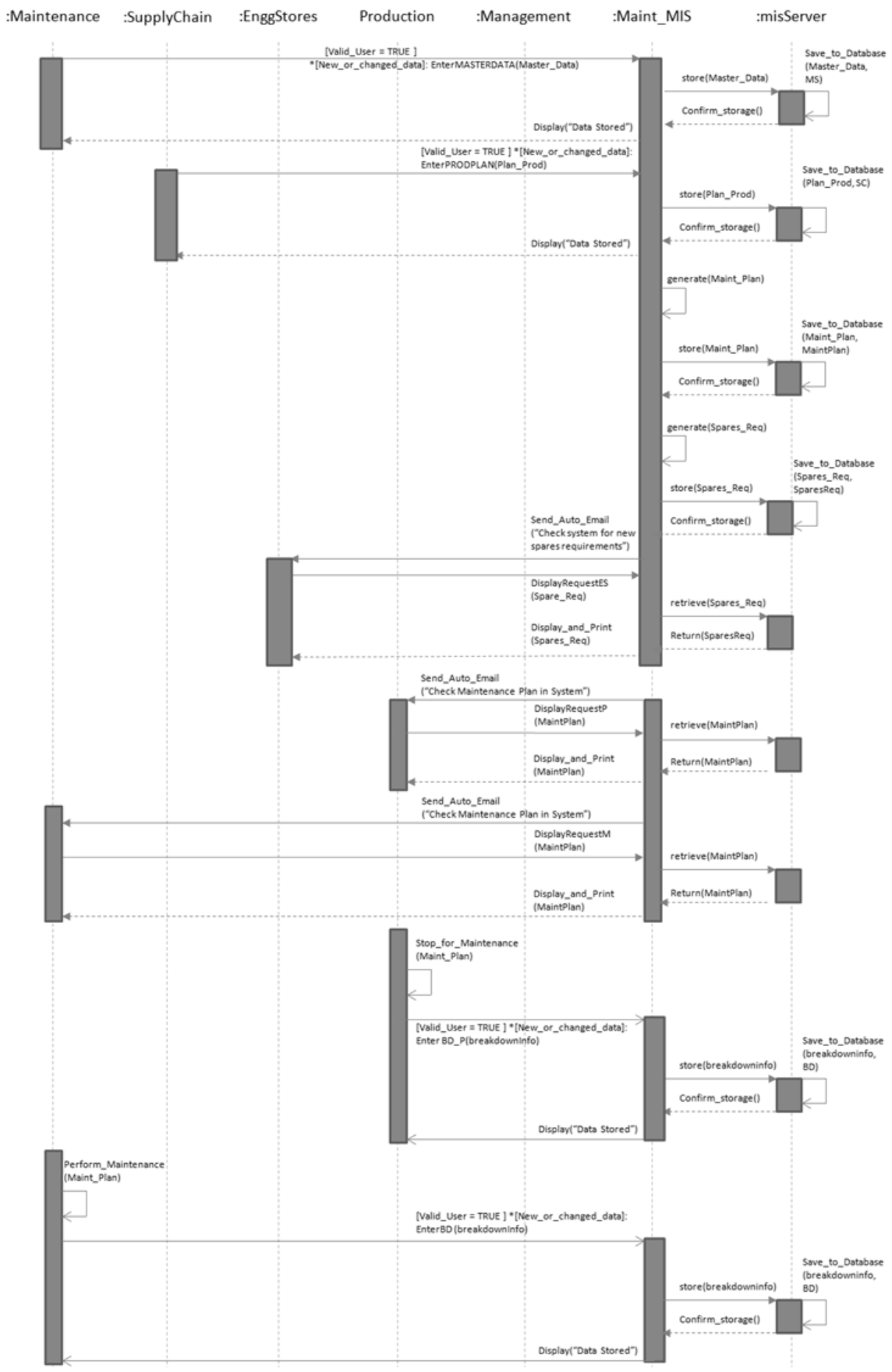

Figure 22: Overall sequence diagram part 1

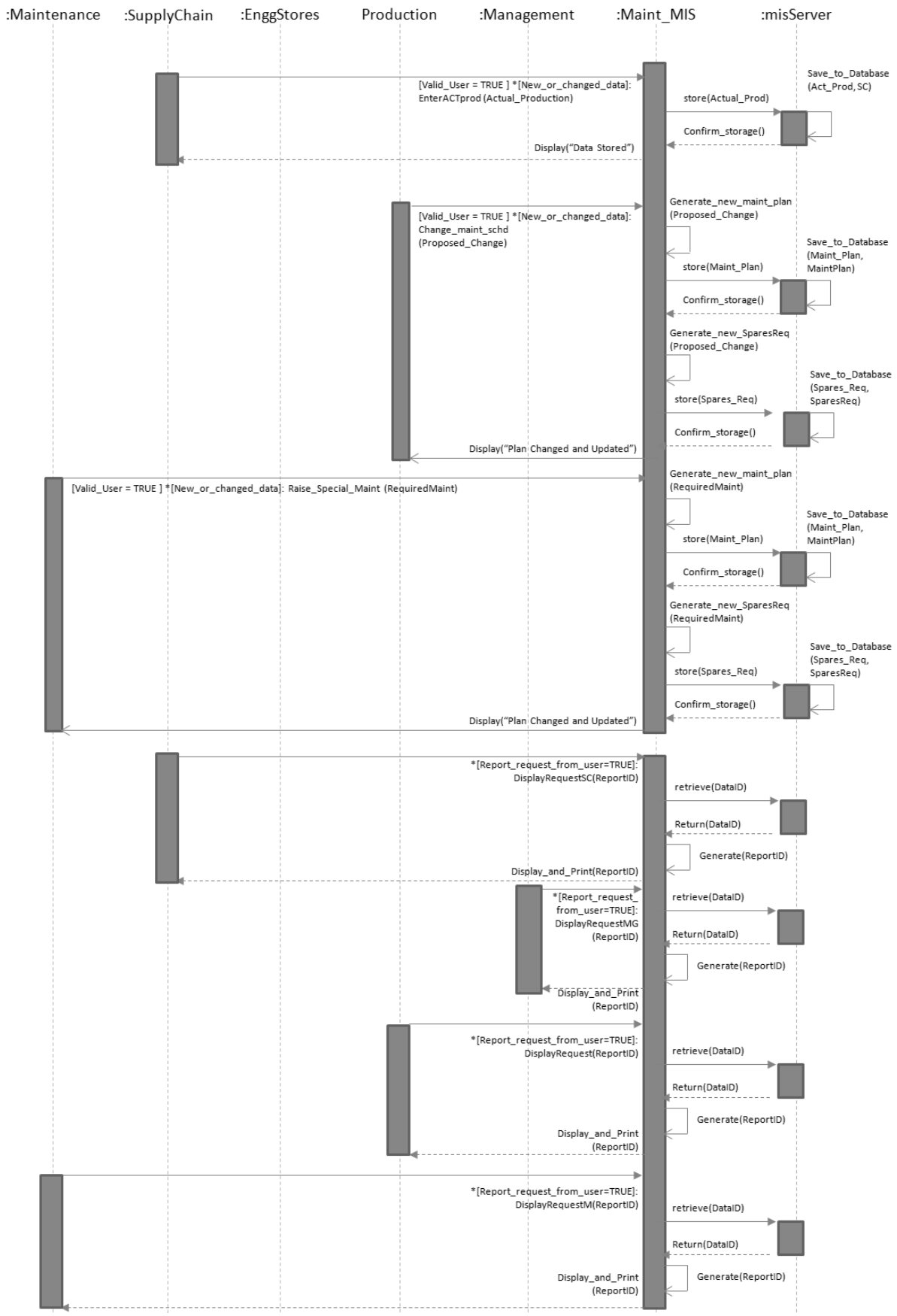

Figure 23: Overall sequence diagram part 2

ERD - ENTITY RELATIONSHIP DIAGRAMS:

An entity-relationship diagram (ERD) is a graphical representation of an information system that shows the relationship between people, objects, places, concepts or events within that system. An ERD is a data modeling technique that can help define business processes and can be used as the foundation for a relational database.

Three main components of an ERD are the entities, which are objects or concepts that can have data stored about them, the relationship between those entities, and the cardinality, which defines that relationship in terms of numbers. The three main cardinal relationships are:

- One-to-one (1:1). For example, if each customer in a database is associated with one mailing address.
- One-to-many (1:M). For example, a single customer might place an order for multiple products. The customer is associated with multiple entities, but all those entities have a single connection back to the same customer.
- Many-to-many (M:N). For example, at a company where all call center agents work with multiple customers, each agent is associated with multiple customers, and multiple customers might also be associated with multiple agents.

Following are the ERDs for the project.

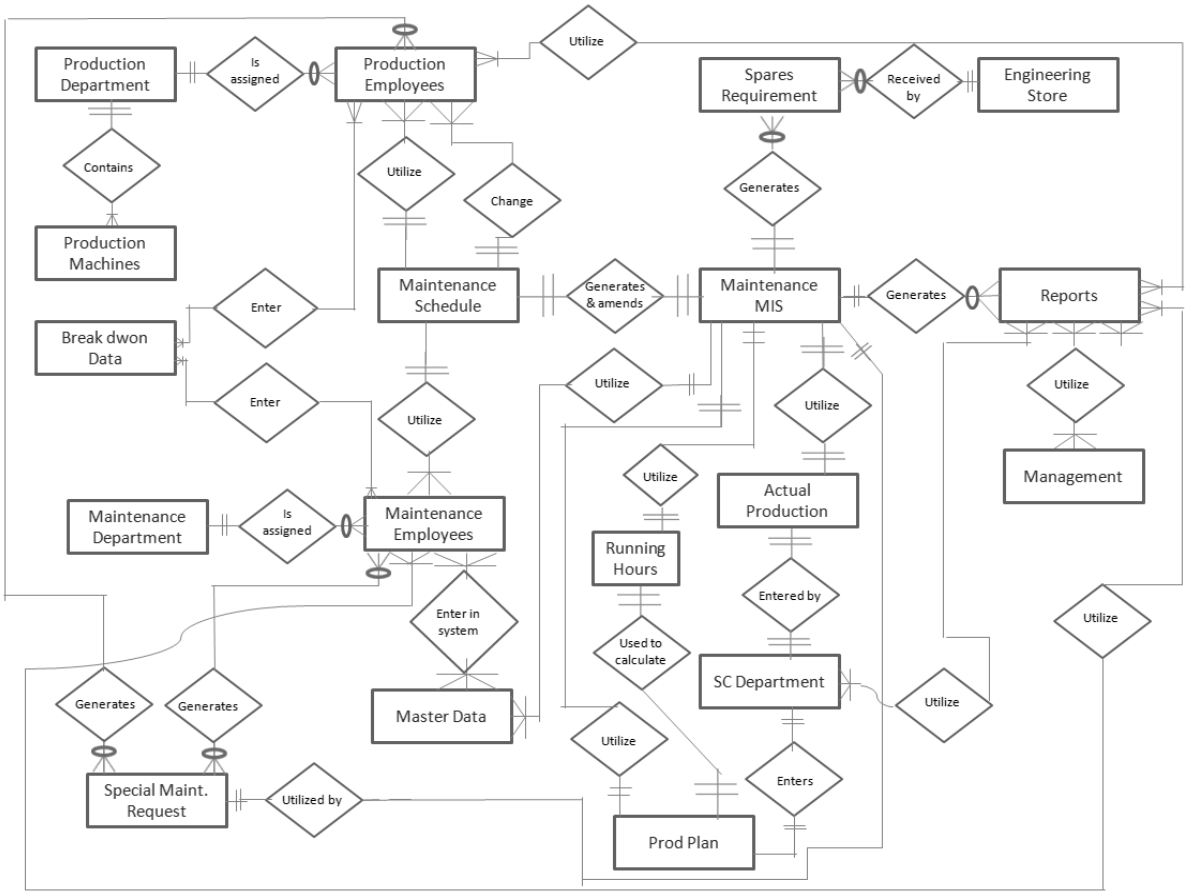

Figure 23: Entity relationship diagram

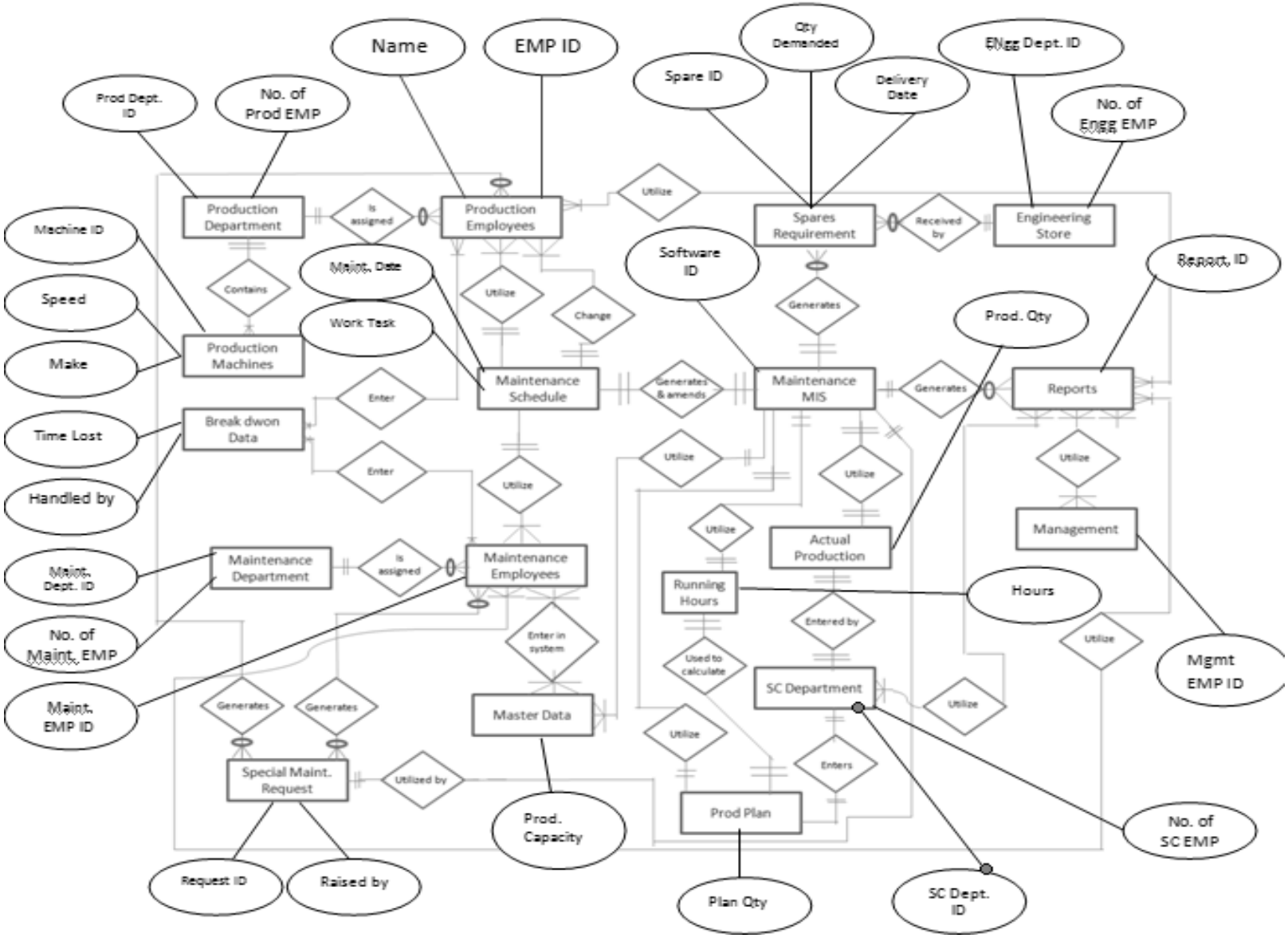

Figure 24: Elaborated Entity relationship diagram

CLASS DIAGRAM:

In software engineering, a class diagram in the Unified Modeling Language (UML) is a type of static structure diagram that describes the structure of a system by showing the system's classes, their attributes, operations (or methods), and the relationships among objects.

In the diagram, classes are represented by boxes that contain three compartments:

The top compartment contains the name of the class. It is printed in bold and centered, and the first letter is capitalized.

The middle compartment contains the attributes of the class. They are left-aligned and the first letter is lowercase.

The bottom compartment contains the operations the class can execute. They are also left-aligned and the first letter is lowercase.

In the design of a system, a number of classes are identified and grouped together in a class diagram that helps to determine the static relations between them. With detailed modeling, the classes of the conceptual design are often split into a number of subclasses.

To avoid graphical congestion, CLASS constituents are not mentioned in the following the figure. However, they have elaborated in the next.

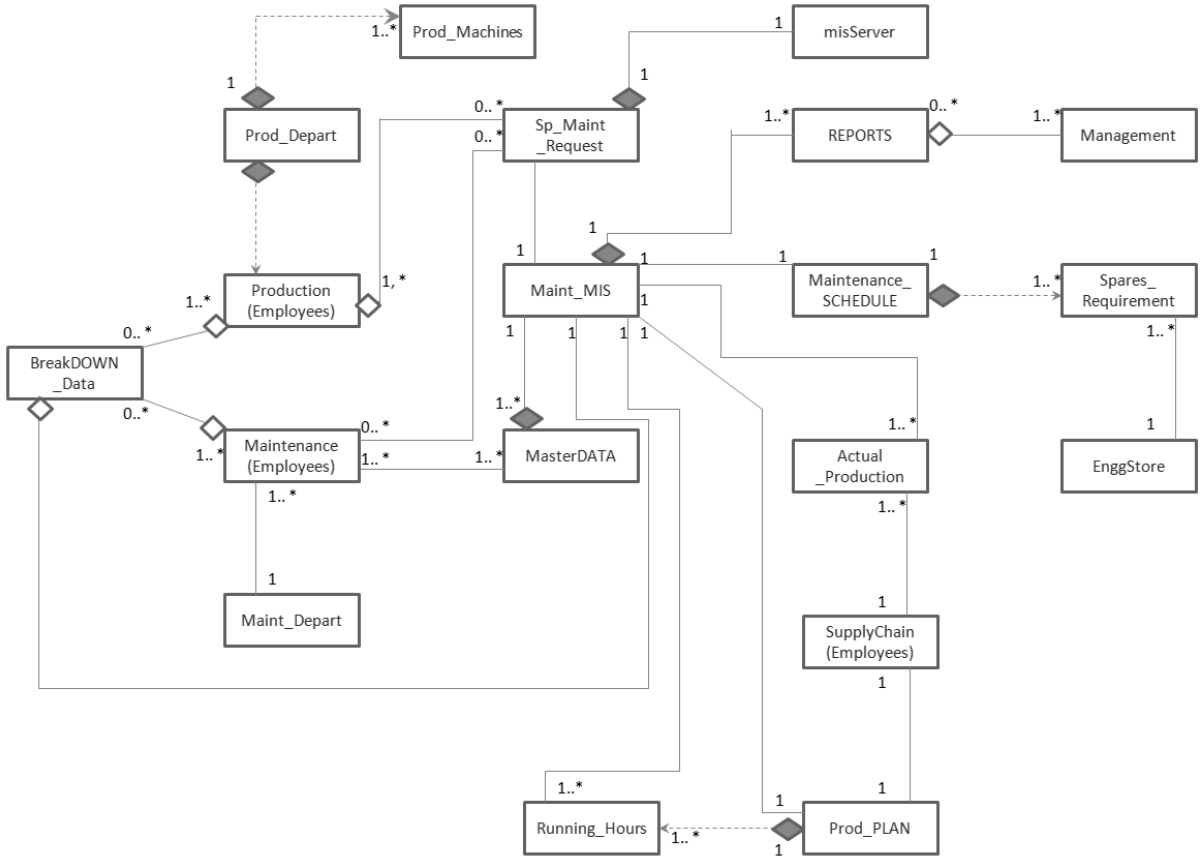

Figure 25: Broad overview class diagram

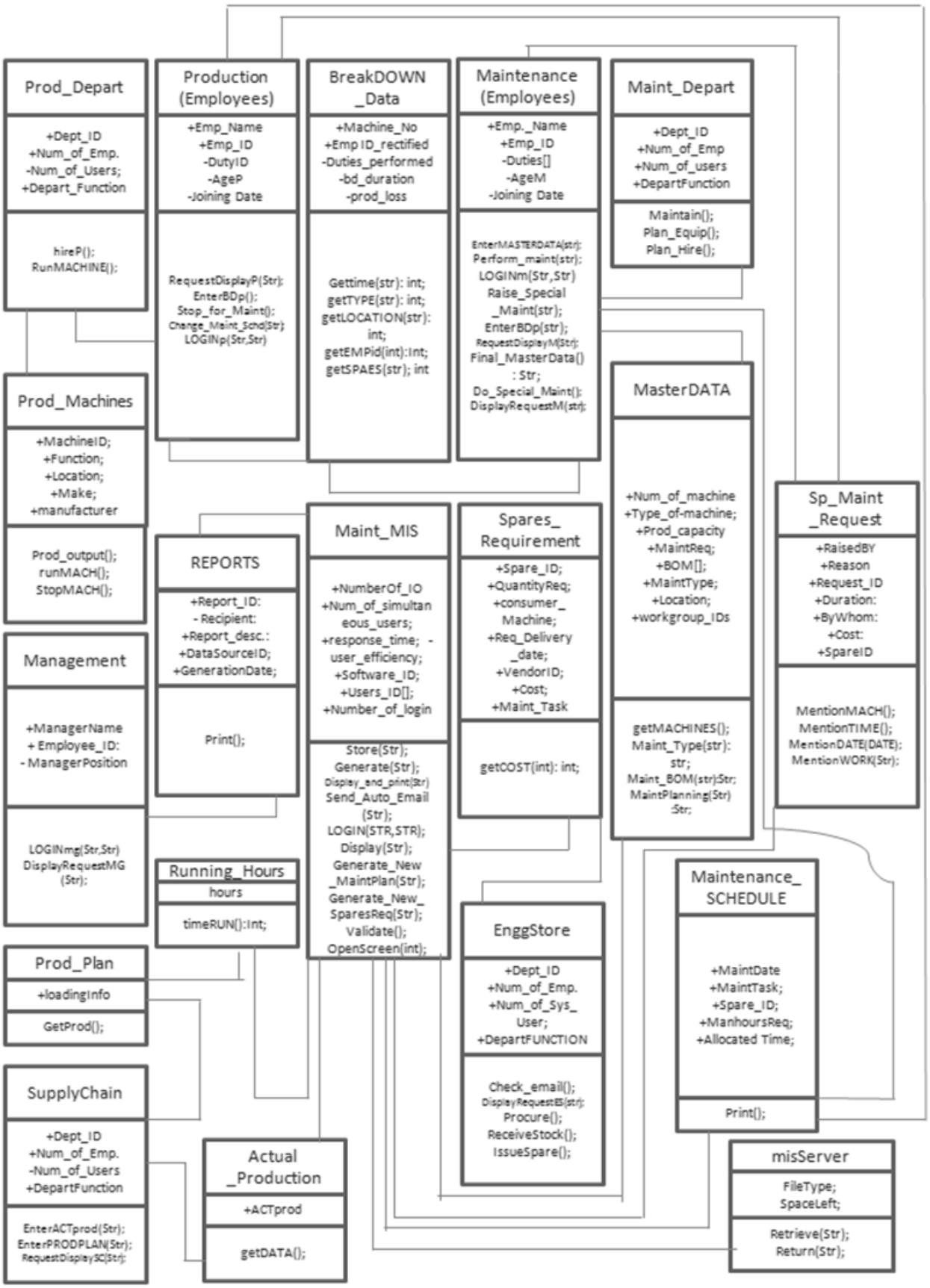

Figure 26: Detailed Class Diagram

DATABASE DIAGRAM:

A database diagram is a type of data model that determines the logical structure of a database and fundamentally determines in which manner data can be stored, organized, and manipulated.

We can see that some data is required for more than 1 function. In such situation, if system collects two sets of data, it would be catastrophic. Accordingly, in database diagram, it is mapped and accordingly planned in terms of organization and storage.

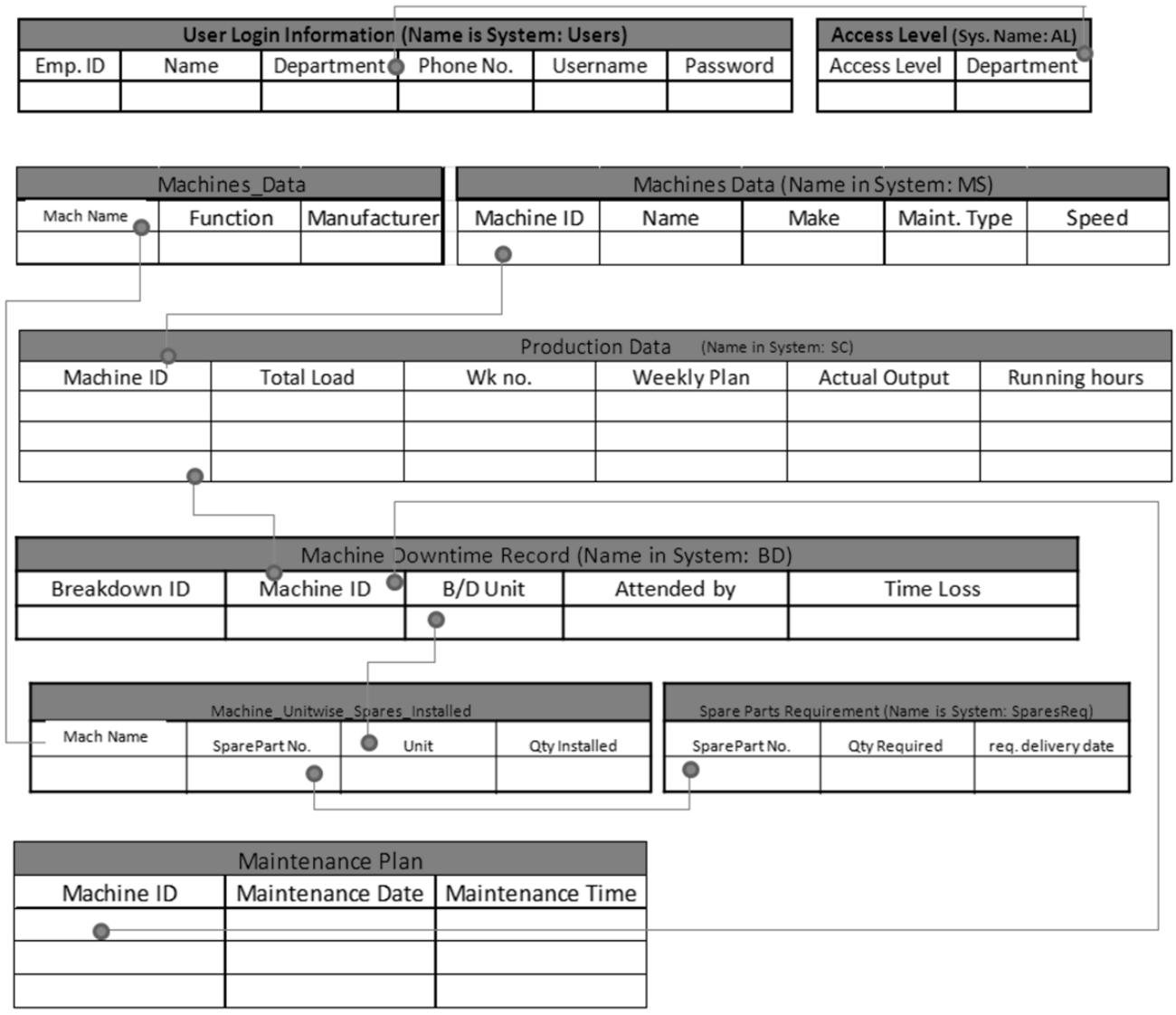

Figure 27: Database Diagram

TEST CASES:

A test case has components that describe an input, action or event, and an expected response, to determine if a feature of an application is working correctly ("How to write effective Test cases?," 2016). Writing effective test cases is a skill and that can be achieved by some experience and in-depth study of the application on which test cases are being written.

Following are test-cases for the current project.

Test Cases	
Title	Testing the Login Mechanism of Maintenance MIS System
Actions	Create user login Go to the Login screen Enter Login Name and Password Press Proceed Button
Expected Results	System Checks if the user is valid or not; If the user is valid, system logs in
Tested by	*To be updated at the time of test*
Result	*To be updated after the test*
Title	View System Generated Reports
Actions	Login to the system From the home screen, select 'View Reports' Select the required report Click Ok
Expected Results	System Checks if the user is valid or not; If the user is valid, system logs in; If above mentioned steps are performed correctly, requested report is shown on the screen
Tested by	*To be updated at the time of test*
Result	*To be updated after the test*
Title	*Enter Master Data into the system*
Actions	*Login to the system* *From the home screen, select 'Master Data'* *Select the required entry option from master data if modifying existing master data or filling pre-selected attributes* *If new master data element is to be made, select 'new master data' and enter the data in the relevant fields* *Click Ok*
Expected Results	*System Checks if the user is valid or not; If the user is valid, system logs in; System will check the access level; If the person logged in is authorized to build/ modify master data, system proceeds, otherwise, error message appears and software returns back to home screen*
Tested by	*To be updated at the time of test*
Result	*To be updated after the test*
Title	*Enter Production Plan in the system*
Actions	*Login to the system* *From the home screen, select 'SC Module'* *Select the required 'Production Plan' entry option from the list.*

	Enter the data in the relevant fields *Click Ok*
Expected Results	*System Checks if the user is valid or not; If the user is valid, system logs in; System will check the access level; If the person logged in is authorized to work in supply chain module, system proceeds, otherwise, error message appears and software returns back to home screen*
Tested by	*To be updated at the time of test*
Result	*To be updated after the test*
Title	*Checking Spare Part demand from the system*
Actions	*Login to the system* *From the home screen, select 'Engineering'* *Select the required 'Spares Demand' option from the list.* *Select from the given options including 'urgently required', 'for making machines', 'for making machines' or 'all requirements'* *Click Ok*
Expected Results	*System Checks if the user is valid or not; If the user is valid, system logs in; System will check the access level; If the person logged in is authorized to work in Engineering module, system proceeds, otherwise, error message appears and software returns back to home screen*
Tested by	*To be updated at the time of test*
Result	*To be updated after the test*
Title	*Checking Maintenance Plan from the System*
Actions	*Login to the system* *From the home screen, select 'Maintenance Schedule'* *Select from the given options including 'One week', 'fortnightly', 'monthly', 'Special maintenance' or 'all'* *Click Ok*
Expected Results	*System Checks if the user is valid or not; If the user is valid, system logs in; If type of maintenance plan view required is not picked from the list, system gives an error message and requests for selection;* *If correct selection is made, system shows the plan on screen*
Tested by	*To be updated at the time of test*
Result	*To be updated after the test*
Title	*Change Maintenance Plan*
Actions	*Login to the system* *From the home screen, select 'Plant Maintenance' Module* *Select from the given options 'Change Maintenance Schedule'* *Enter relevant data in the form opened* *Click Ok*
Expected Results	*System Checks if the user is valid or not; If the user is valid, system logs in;*

	The system checks the access level and if found ok, proceeds with the data entry. *When the submit button is pressed, system generates new maintenance plan and notifies the stakeholders about the change*
Tested by	*To be updated at the time of test*
Result	*To be updated after the test*
Title	*Raise Special Maintenance Request*
Actions	*Login to the system* *From the home screen, select 'Plant Maintenance' Module* *Select from the given options 'Special Maintenance'* *Enter relevant data in the form opened* *Click Ok*
Expected Results	*System Checks if the user is valid or not; If the user is valid, system logs in;* *The system checks the access level and if found ok, proceeds with the data entry.* *When the submit button is pressed, system generates new maintenance plan and notifies the stakeholders about the change*
Tested by	*To be updated at the time of test*
Result	*To be updated after the test*
Title	*Enter Breakdown Data*
Actions	*Login to the system* *From the home screen, select 'Plant Maintenance' Module* *Select from the given options 'Breakdown Maintenance'* *Enter relevant data in the form opened* *Click Ok*
Expected Results	*System Checks if the user is valid or not; If the user is valid, system logs in;* *The system checks the access level and if found ok, proceeds with the data entry.* *When the submit button is pressed, system shows analysis of the breakdown and recovery process*
Tested by	*To be updated at the time of test*
Result	*To be updated after the test*

CONCLUSION:

In this paper, we have presented the design of a simple but effective maintenance information management system with various phases during the design except software coding which would be a futile effort without customizing the model and phases according to specific organizational and company specific factors. The scope of functions can also be adjusted to include relevant requirements. The proposed model can also be used for base-level evaluation of existing Maintenance information systems and utilized for implementing continuous improvement initiatives. It is also to be noted that for the full ERP, a number of other aspects will need to be included.

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DESIGN OF MECHATRONICS ENGINEERING ASSOCIATE DEGREE PROGRAMS – AN OVERVIEW

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ABSTRACT

After reviewing Mechatronics programs from numerous international educational organizations, this proposed course outline and unit descriptions have been prepared for associate degree programs in Mechatronics engineering. Over the period of more than two months, we have carefully analyzed and reviewed relevant program details including required courses and their outlines, pre and co-requisites, labs work requirements and other relevant details. A time-frame of 8 to 10 months is required for starting the first batch of Mechatronics Associate degree in colleges where Mechanical and Electrical/ Instrumentation programs are already being offered. It is because this program employs a multi-disciplinary approach and necessitates a synthesis of disciplines. However, this recommended time to commence the course offering after necessary design and development steps can vary significantly depending on the status of existing courses and their alignment with objectives associated with Mechatronics courses. Recommendations produced in this paper include relevant objectives from the programs and proposed units in alignment with ABET Engineering Accreditation Commission's criteria for the year 2016-17.

INTRODUCTION

In the rapidly changing economic scenarios in the modern world, Industrialization remains the strategic choice in accelerating the achievement of economic development objectives (Kniivilä, 2007). Advances in industrialization, in turn, are heavily dependent on technological progress. Technology dimensions are expanding at a very rapid pace (Basalla, 1988; Geels, 2005; Jenkins & Floyd, 2001; Nelson, 1994). This poses a major challenge to technology education institution to keep their students well versed with the modern industrial processes and technology innovations (Holbrook, 2009; Sjøberg, 2002; West, 1999). Industries are moving towards flexible mechanisms for the improvement in design, production, planning and engineering design. This has started an era of 'cross-functional thinking' (Davenport, Short, & others, 1990; Holland, Gaston, & Gomes, 2000; McDonough, 2000) and 'collaborative approach' (Bychkovskiy, Megerian, Estrin, & Potkonjak, 2003; Highsmith, 2013; Jones, Rasmussen, & Moffitt, 1997; Mishne, 2006) for industrial problem solving. This requires various engineering disciplines to come together and work collaboratively to meet the future challenges.

Mechatronics is a discipline that can bridge the existing divide between electrical/instrumentation and mechanical engineers fostering an innovative culture and yielding more cross-functional productivity improvements initiatives. Mechatronics is a synergistic approach aiming at the integration of mechanics, electronics, control theory, and computer science within product design and manufacturing, in order to improve and optimize industrial applications and processes (Kyura & Oho, 1996). In a didactic approach to mechatronics, the academic subject can be defined according to four dimensions: identity, legitimacy,

selection and communication. A result of defining the legitimacy of mechatronics as functional is that the ultimate identity can be viewed as thematic (Grimheden & Hanson, 2005).

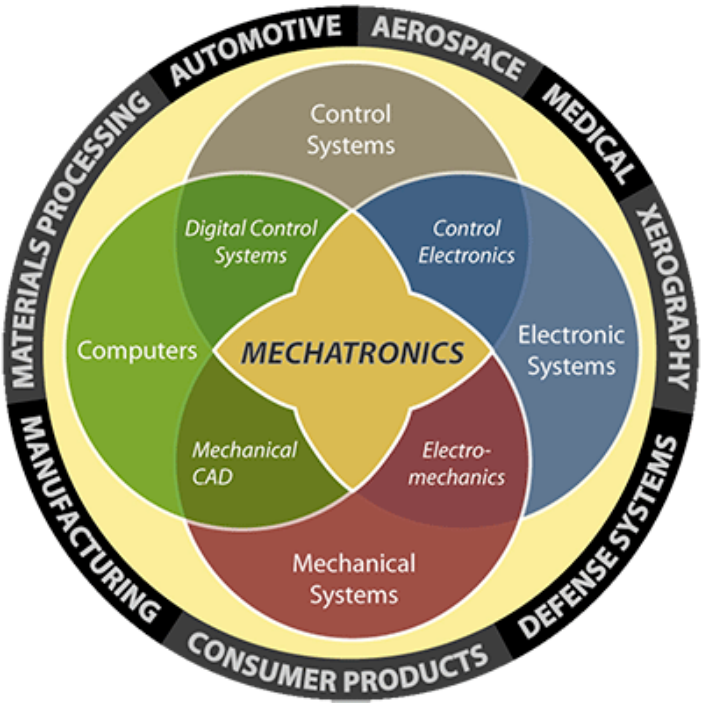

Figure 1 Mechatronics as a synergistic approach

Mechatronics is a multidisciplinary approach and requires integration between different engineering and technology branches in order to produce intelligent systems. Some common industrial examples of Mechatronics systems include:

- Automation (PLCs, Microcontrollers etc)
- Machine Vision Systems
- Manufacturing of electronics equipment
- Robotics Design and Operation
- CNCs Machining Systems
- SCADA Systems
- Machinery Diagnostics
- Consumer Products Industry
- Product and Process Quality Assurance

High levels of automation in manufacturing and service environments require a multi-disciplinary approach. Systems have sophisticated mechanical designs and require automation system designer to have a background in mechanical sciences as well. Most of the projects and service tasks fail because of lack of knowledge or coordination in the working team. Mechatronics engineering is meant to bridge this industrial skill gap. Graduates from this program are expected to add great value to industries they work for because of their diversified engineering knowledge and hands-on training.

Many industrial colleges offer effective technology programs in the disciplines of Mechanical, Electrical and Computer Engineering which cover different aspects of Mechatronics technology program. The curriculum for Mechatronics programs is designed in a way to SYNERGISE these skills, keeping in mind the industrial requirements.

While proposing the framework for this associate degree program, we have considered relevant requirements from ABET. ABET, incorporated as the Accreditation Board for Engineering and Technology, Inc., is a non-governmental organization that accredits post-secondary education programs in "applied science, computing, engineering, and engineering technology" (“About Abet | ABET,” 2016). ABET currently accredits 3,569 programs at 714 colleges and universities in 29 countries. It is to be noted that the current list of engineering technology or associate degree programs that can be recognized by ABET does not include Mechatronics. However, it can be offered under other relevant titles such as Electro-mechanical engineering technology or instrumentation and control systems engineering. Adjustment in units may be required to accommodate needs to these specific programs.

In this proposed program framework, we have covered relevant details from the accreditation criteria with regards to course objectives, student outcomes, and curriculum design. However, there are other aspects as well which need compliance before the accreditation is achieved. Institutions planning to comply for accreditation will need to go through all relevant requirements and ensure compliance. Another important aspect to consider in this regard is the changes in accreditation criteria over the years. The current proposal is based on criteria for the year 2016-17. In subsequent years, latest version at that time should be followed.

PROGRAM OBJECTIVES AND OUTCOMES

Based on our research, we propose following objectives for the program.

In line with ABET accreditation requirements, programs are required to have well-defined objectives. According to ABET, “Program educational objectives are broad statements that describe what graduates are expected to attain within a few years after graduation. Program educational objectives are based on the needs of the program’s constituencies” (“Criteria for Accrediting Engineering Technology Programs, 2016 – 2017 | ABET,” 2016). ABET’s accreditation criteria in this regard stipulate that “the program must have published program educational objectives that are consistent with the mission of the institution, the needs of the program’s various constituencies, and these criteria. There must be a documented, systematically utilized, and effective process, involving program constituencies, for the periodic review of these program educational objectives that ensures they remain consistent with the institutional mission, the program’s constituents’ needs, and these criteria” (“Criteria for Accrediting Engineering Technology Programs, 2016 – 2017 | ABET,” 2016).

Objective of Mechatronics Technology Associate program is to enable its graduates to:

- Assume entry level position in industries to deliver services and support to internal and external clients by applying technical knowledge, problem solving and hands-on skills, in traditional and emerging areas of Mechatronics and related disciplines.

- Adapt to changes in technology and proactively apply current knowledge and problem-solving skills in order to support mechatronics and other relevant system components.

- Perform professional activities with integrity, a sense of social, ethical and environmental responsibility, attention to safety and occupational health, teamwork, and effective communication.

- Demonstrate success in the chosen careers through promotion, occupational mobility, and demonstration of leadership skills in their organizations and professions.

- Achieve professional excellence and knowledge advancement through higher education, on-job training, and relevant certifications.

Following Outcomes are expected from Mechatronics Technology Program. According to ABET, "Student outcomes describe what students are expected to know and be able to do by the time of graduation. These relate to the knowledge, skills, and behaviors that students acquire as they progress through the program" ("Criteria for Accrediting Engineering Technology Programs, 2016 – 2017 | ABET," 2016). ABET's criteria in this regard state that the program must have documented student outcomes that prepare graduates to attain the program educational objectives. There must be a documented and effective process for the periodic review and revision of these student outcomes.

ABET requires following outcomes from the programs:

a) an ability to apply the knowledge, techniques, skills, and modern tools of the discipline to narrowly defined engineering technology activities;
b) an ability to apply a knowledge of mathematics, science, engineering, and technology to engineering technology problems that require limited application of principles but extensive practical knowledge;
c) an ability to conduct standard tests and measurements, and to conduct, analyze, and interpret experiments;
d) an ability to function effectively as a member of a technical team;
e) an ability to identify, analyze, and solve narrowly defined engineering technology problems;
f) an ability to apply written, oral, and graphical communication in both technical and non-technical environments; and an ability to identify and use appropriate technical literature;
g) an understanding of the need for and an ability to engage in self-directed continuing professional development;
h) an understanding of and a commitment to address professional and ethical responsibilities, including a respect for diversity; and
i) a commitment to quality, timeliness, and continuous improvement.

In accordance with above, following is a set of proposed student outcomes from associate engineering degree level courses in mechatronics. Students from Mechatronics courses at associated degree level should be able to:

- Apply the principles of mathematics and applied science to perform technical calculations and solve technical problems of the types commonly encountered in mechatronics engineering technology. (Consistent with ABET criterion 3, points a-e)
- Be able to perform competently in a laboratory setting, taking measurements, operating technical equipment, critically examining and reporting experimental results, and indicating the potential for process improvements. (Consistent with ABET criterion 3, points a-e, i)

- Be able to use modern computational tools for technical problem solving including scientific calculators, relevant lab equipment, computers and technical software. (Consistent with ABET criterion 3, points a, c)

- Be able to demonstrate broad basic education and knowledge of contemporary issues in global and societal contexts as required to develop professional and ethical responsibility to employers and society at large. (Consistent with ABET criterion 3, points a, b, d, g, f)

- Be able to recognize the need for life-long learning and continuous professional development in the field of mechatronics engineering technology. (Consistent with ABET criterion 3, points g, h)

- Be able to demonstrate the ability to communicate and function effectively with members of multi-disciplinary teams and other members and workers from various backgrounds in an industrial setup. (Consistent with ABET criterion 3, points d, f)

- Be able to demonstrate a commitment to quality, punctuality, and continuous improvement. (Consistent with ABET criterion 3, point I, criterion 4)

- Be able to demonstrate proficiency in technical knowledge and skills, effective communication, and strength of character in order to take up supervisory and other leadership roles in the industry. (Consistent with ABET criterion 3, points f, g, h)

STUDY PLAN - CURRICULUM DESIGN APPROACH:

Study Plan for Mechatronics Engineering Technology Program is developed through the following:

- Detailed review of courses from renowned universities worldwide
- Specific and relevant industrial skills needs for the kingdom addressed
- Gradual student skill development process followed
- PROJECT/ practical based approach (one project per semester) in order to equip Mechatronics students with hands-on knowledge and problem-solving abilities
- Laboratory activities are an integral part of the program and include tutorials, case studies, group discussions, role model exercises, video exhibits and visits to renowned industrial establishments.

Units:

Units are structured as per figure 2.

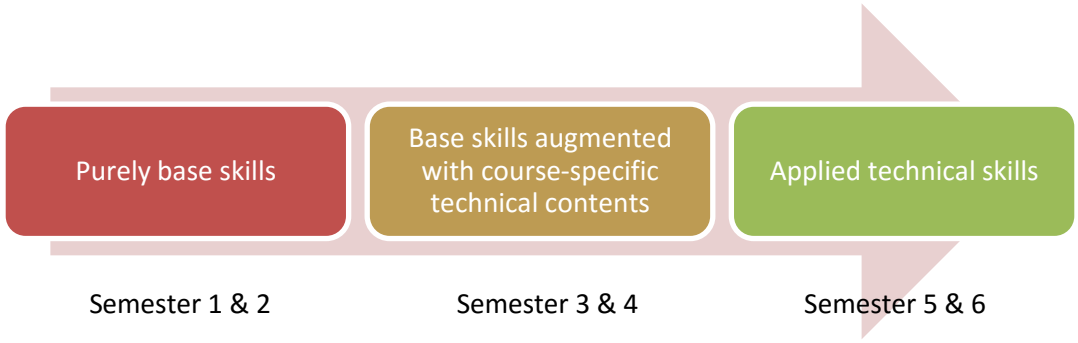

Figure 2 Associate Degree Progressions

It is to be noted that ABET criterion 5, TECHNICAL CONTENT – point a states that key technical content has to be more than 1/3 of the total program but should not be more than 2/3. Our proposed structure adheres to this requirement as explained in figure 2.

ABET criterion 5, TECHNICAL CONTENT – point b requires that program should "include a technical core that prepares students for the increasingly complex technical specialties they will experience later in the curriculum." We have ensured a gradual progression of learning and cohesion by exposing students to core skills required for more advanced courses they are going to work with in later semesters.

Our courses, complemented with labs, with also satisfy ABET criterion 5, TECHNICAL CONTENT – point c which requires the development of student competency in the use of equipment and tools common to the discipline.

Semester 1 and 2:

In semester 1 and 2, we propose units that help students in gaining core study skills including 'proficiency in English language', 'introduction to technology (basic engineering skills including workshop operations, welding, machining etc.), mathematics (algebra and trigonometry), physical education, drafting and introduction to computing for mechatronics applications.

It is to be noted that ABET accreditation criteria 5, which specifies details about the curriculum for associate degrees requires mathematics education to include algebra and trigonometry. Proposed course selection will address ABET Criterion 5, MATHEMATICS - point a.

Semester 3 and 4:

In semester 3, English language skills can be developed further with a focus on communication and composition. Mathematics skills should focus on calculus to prepare students for subjects coming in later semesters. Physics can be included to assist students with electronics related subjects. In this

semester, students can also be exposed to electronics circuit fundamentals. Graphics skills can be progressed further with the inclusion of drafting techniques for mechatronics design.

In semester 4, chemistry can be included. It can be swapped with physics in semester 1/2 if required. Mathematics skills can be advanced by adding units on calculus. It is to be noted that it is in accordance with ABET Criterion 5 in terms of including physical/ natural sciences in the curriculum.

From mechatronics units, semester 4 seems to be the suitable option for inclusion of units on 'Applied Mechanics' and 'Mechatronics measurements'. Electronic circuit fundamentals introduced in previous semesters can be progressed further by the inclusion of a unit on 'Introduction to electronics'.

Semester 5:

By this time, students would have acquired basic mechanical and electronics skills in addition to key engineering study skills. In semester 5 and 6, this knowledge can be applied to acquire deeper and more applied skills in the discipline.

In semester 5, we recommend inclusion of subjects on 'Maintenance and troubleshooting', 'Mechatronics fundamentals', 'Mechatronics systems', 'Digital electronics' and 'engineering programming'.

As we go more into applied aspects of the discipline, a course on industrial safety can be very suitable for this semester. Also, mathematics skills for more advanced calculations can be progressed with a unit on 'applied differential equations'.

Semester 6:

Semester 6 continues with applied skills.

Based on programming skills acquired in semester 5 and combining it with the knowledge of digital electronics, students can now study 'Microcontrollers and Microprocessor applications'.

Students can also be given the opportunity to advance their skills in 'Industrial Electronics', 'Control Systems' and 'Mechatronics systems' by the inclusion of relevant units on these subjects. Mechatronics systems can act as an umbrella unit which can include a number of relevant areas based on specific priorities of local industries and engineering education provider.

At this stage, we also recommend inclusion of a unit on research methods which should also require students to write a research report.

All students will be required to complete co-operative attachment/ internship at the end of course to gain practical experience. This is also in accordance with ABET criterion 5 in relation to 'cooperative education'.

CONCLUSION AND RECOMMENDATIONS:

In this paper, we have proposed a course framework for Mechatronics engineering associate degree program in line with ABET's criteria for the year 2016-17. This can be a good starting point for organizations planning to launch relevant programs. This is a baseline proposal and further customization and contextualization will be essential before the implementation and course design. Mechatronics is an important skill for current and future industry and effectively designed educational interventions can be very valuable in ensuring high productivity and growth of industrial operations through the deployment of appropriately trained mechatronics graduates and technologists.

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SURFACE WATER TREATMENT IS A BIG CHALLENGE FOR NORTH SINDH - A CASE STUDY OF 18MGD WTP NUMAISHGAH, SUKKUR

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ABSTRACT

To solve the issue of the polluted water supply to Sukkur city, a case study has been taken to assess the quality of the water supplied by 18MGD Water Treatment Plant (WTP) Numaishgah, Sukkur. During the laboratory test, eight parameters were tested. The tests were conducted for a period of ten months from September 2014 through June 2015. In this paper, the performance of WTP is evaluated to assess the quality of water supply at the inlet and outlet of WTP. During the test the maximum values at inlet and outlet for pH of 7.7 and 7.8 respectively were obtained, whereas 360 mg/l and 350 mg/l respectively were measured for TDS, that are within the prescribed limits of 6.5-8.5 for pH and <600 mg/l for TDS suggested by WHO. Furthermore, it has been observed that Escherichia Coliforms is present in every sample of water, which confirms that the water is contaminated by fecal coliforms at the inlet as well as at the outlet. From the study, it is concluded that if the filtration units are rehabilitated, the quality of water can easily be achieved at the outlet of WTP.

Key words: Water treatment, Water supply, Filtration, Numaishgah, Sukkur.

INTRODUCTION

Since the independence of Pakistan, the supply of fresh drinking water has remained a challenge for the concerned authorities, due to the ever growing population [3]. In this regard, a number of measures have been taken till now and those have proved to be very beneficial for the public. Though, still many people are facing problems in acquiring fresh drinkable water.

Water is the necessity of all living things, and thus, in Sindh, the Indus River plays a vital role in the supply of fresh water. But, since the river flows in an alluvial state, the water is not readily consumable [17]. The river also contributes to groundwater, but due to excessive artificial field fertilization, the groundwater is also contaminated. The water from the river is to be treated first so that safe supply of water to the people is ensured.

For the improvement of environmental conditions in Pakistan, the Government of Pakistan started the provincial Planning & Development Departments (P&DD) in 1970. The P&DD Sindh established Municipal Corporations in divisions across the province to regulate the environmental conditions in Sindh. Later on, with the increase in population, the Municipal corporations were found to be not enough to meet the requirements of the public. It was then that the Government was funded by the Asian Development Bank (ADB) [15], and the Sindh Cities Improvement Program (SCIP) was started in the 2000s [14, 15]. The SCIP established Urban Services Corporations (USC) in addition to the existing Municipal Corporations so that the Government can cope up with the loss of environmental regulation [15].

The North Sindh Urban Services Corporation (NSUSC) was established in 2009 and handles the environmental matters such as water supply, wastewater management, and solid waste management for north Sindh [15]. The NSUSC established Water Treatment Plants across Sukkur. At present three water treatment plants located at Bunder road, Airport road and at Numaishgah ground Sukkur are in operation. WTP Numaishgah is situated on rocky stratum as most of the Sukkur City is, and thus, it has to supply water for drinking as well as for other routine activities, while the other two treatment plants i.e. Bunder road and Airport road are situated in areas where groundwater is readily available for routine use, and the said WTPs only supply drinking water [9, 10, 13]. The WTP Numaishgah was established in 2009 as a 2.5MGD plant, but was rehabilitated in 2012 and its capacity was increased to 18MGD [15].

But the problem of contaminated water still persists and most of the public is receiving polluted water in spite of the thorough working of the USCs. The consumption of the polluted water leads to a number of chronic diseases including diarrhea, cholera and dysentery [6].

Here rises the question whether the contaminated water supply in Sukkur city lies in the supply network or in the water treatment plant. According to a study conducted by [10] in 2012, it can be unambiguously inferred that the problem greatly lies within water treatment plants rather than in supply network [1].

Keeping the political, administrative and economic perspectives out, only the environmental engineering perspective has been used in this case study. The performance of the plant has been evaluated to assess the quality of water at the inlet and at the outlet. The results obtained from this study have been compared and benchmarked with the published guidelines on acceptable drinking water quality by the WHO.

OPERATION OF THE 18MGD WTP NUMAISHGAH

The water is pumped from the River Indus into the treatment plant by a number of pumps installed at the Bunder road pumping station. The water is inlet directly into the sedimentation tanks where it stays for a while; in the meantime alum is added. The water is then pumped out directly to the Islamia College distribution reservoir and the Adam Shah Colony distribution reservoir that distribute the water around the city.

In the rehabilitation process, Rapid sand filters, screens, and chlorination plant were established, but these have not been added to the treatment chain of the plant yet.

Samples were collected and tested twice daily at the inlet and at the outlet that are in the sedimentation tank and after the pumps respectively. In this study, a data of about 10 months i.e. from September 2014 to June 2015 has been analyzed.

METHODOLOGY

Table 1 shows the conventional methods of testing water samples as used in the testing of water at the Environmental Engineering lab of 18MGD WTP Numaishgah. Depending upon the measuring instruments available, the following parameters of water quality were able to be tested.

Parameter	Testing Method
Turbidity	Nephelometer
TDS	Conductivity meter
pH	Potentiometer
E. Coliforms	Sulfur-Brath test
Colour	Tintometer
Taste	Physically/Tongue
Odour	Omoscope
R/Chlorine	Horrock's Test

Table 1 | Methods of testing water samples

WHO GUIDELINES

Table 2 provides the water quality parameters with their limits for the acceptable quality of the drinking water published by The World Health Organization [16] in the guidelines for drinking water quality.

Parameter	WHO Standard
Color	< 15 TCU
Taste	Pleasant to taste
Odour	Pleasant to smell
Thermotolerant (Faecal) Coliforms	0
Total Dissolved Solids (TDS)	<600 mg/l
pH	6.5-8.5 [16]
Turbidity	< 5NTU
Chlorine	5 mg/l (Health)

Table 2 | WHO guidelines for drinking water quality

RESULTS & DISCUSSION

a. Turbidity

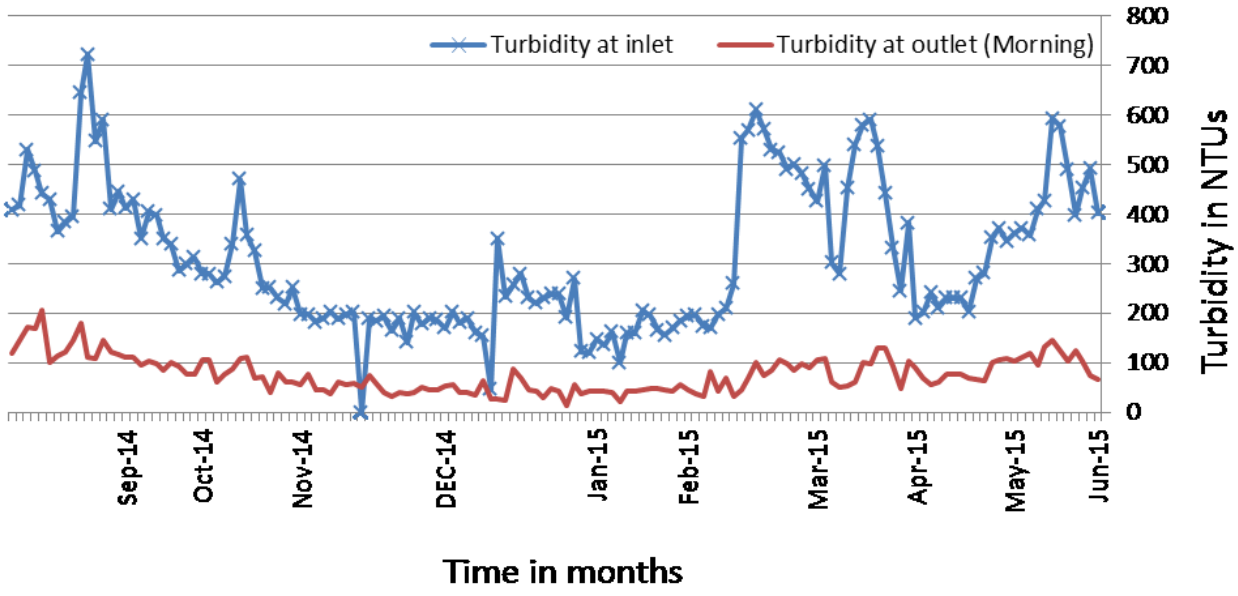

Figure 1 | Variation of turbidity at inlet and outlet of the WTP

Discharge in River Indus is increased in summer and decreased in winter, this affects the quality of water by a slight margin as stated in [17 , 20]

Turbidity is found to be varying in a directly proportional pattern with the discharge in the river. Increased turbidity is an indication of increased discharge in the river, since the increased discharge causes excessive erosion and less silting [17], and the opposite is the case in times of low discharge.

It is thus found that irrespective of the inlet values, the values of turbidity at the outlet are always in the range of 50NTU – 150NTU, which are far beyond the WHO guidelines that allow a maximum turbidity of 5NTU at the outlet [16].

These increased values at the outlet show that a sufficient amount of alum is not added to the water in the sedimentation tanks so as to accelerate the process of coagulation and flocculation [4].

b. Total Dissolved Solids (TDS)

Figure 2 presents the TDS values at the inlet and outlet from September 2014 to June 2015. The figure shows the total dissolved solids are found to be varying in an inversely proportional pattern with the discharge in the river as stated before [17, 20]. It can be inferred that the increased discharge dilutes the total salt concentration of the river.

The values of TDS at the inlet and the outlet are the same and average to about 300mg/l but are unfortunately in the limits of the WHO guidelines that allow a maximum value of 600mg/l TDS at the outlet [16].

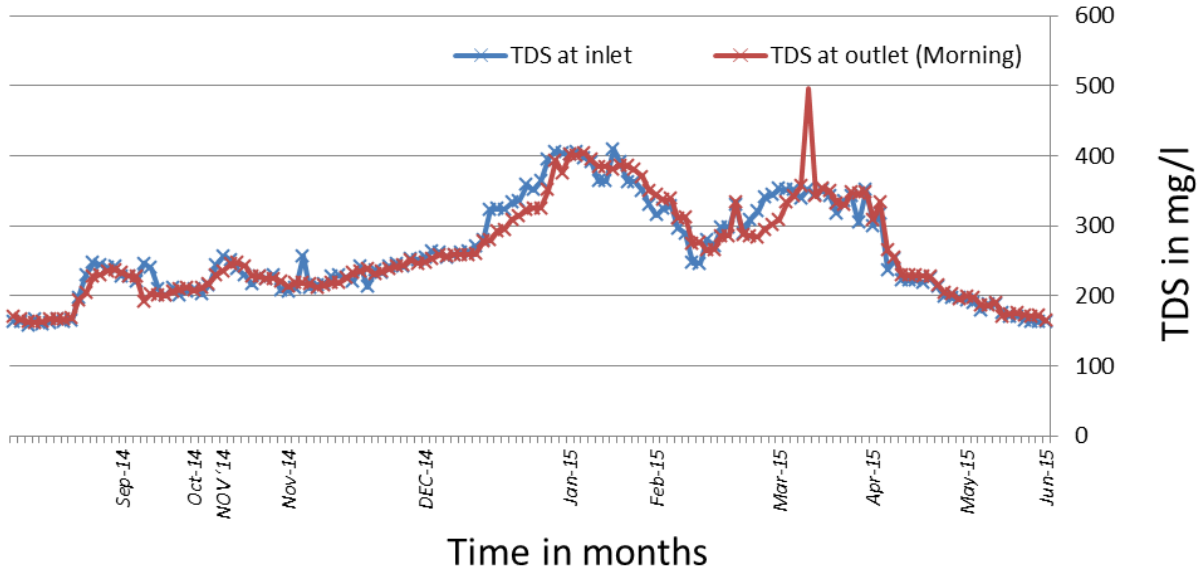

Figure 2. Variation of TDS at inlet and outlet of the WTP

c. 5.3 pH

In Figure 3, the values of pH at inlet seem to vary in a directly proportional pattern with the discharge in the river, and in increased discharge, the river turns basic due to dilution. As stated in [18 , 19], the river is highly contaminated with fecal coliforms which forces the pH of the water to drop down, the excess discharge dilutes this concentration and increases the pH values.

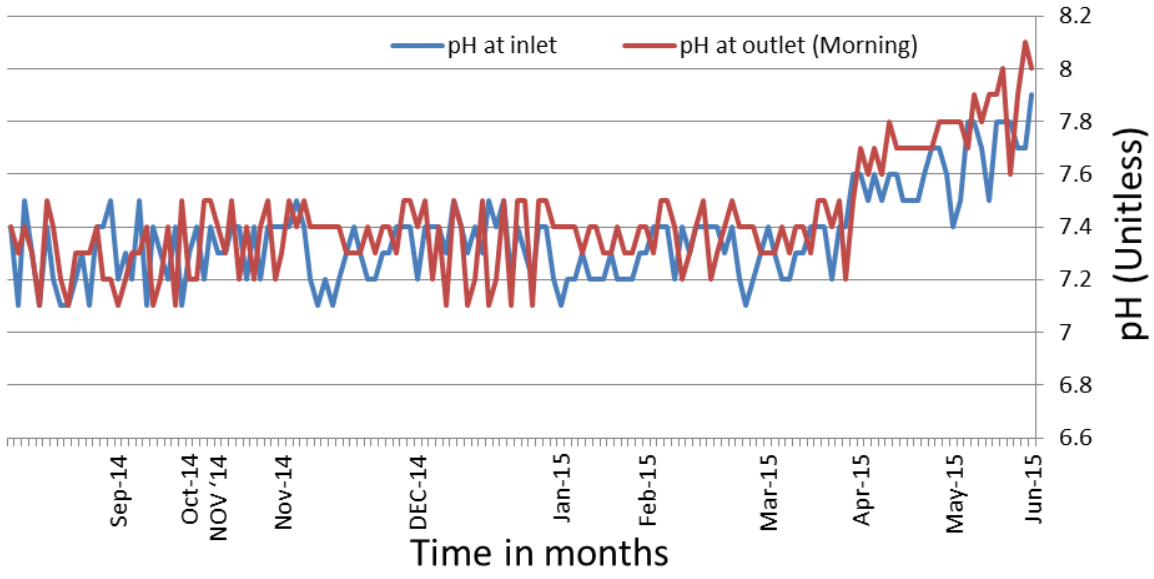

Figure 3 Variation of pH values at the inlet & outlet of WTP.

It is also observed from figure 3 that the values of pH at the inlet are slightly more than the values at the outlet of the treatment plant, which indicates improper treatment and the addition of salts inside the treatment plant. However, the values of pH at the inlet and outlet are in the limits put forward by the WHO i.e. 6.5 – 8.5 [16]. The main cause of destabilized pH values is the absence of sand filters.

d. Coliforms

From the results of Sulfur-Brath test conducted on samples, E. Coliforms were found to be present in every sample of water taken either at the inlet or at the outlet; this indicates contamination of water by fecal coliforms at the inlet and at the outlet.. [19] explains the phenomenon of contamination at the inlet source that the Indus River is polluted along all the big cities surveyed. The samples at the outlet are contaminated because water is not being treated in the treatment plant e.g. in a sand filter, nor is chlorine being added. As per WHO guidelines, there must be no biological contamination and the number of bacterial colonies must be zero [16].

e. Residual Chlorine

The Horrock's test conducted on every sample of water shows that the Residual Chlorine is absent in all the samples at the outlet, and it is equally true because the chlorination plant is not working. As per WHO guidelines, a minimum 5mg/l of chlorine must be present in the water at the outlet of a treatment plant.

f. Colour

All of the samples examined at the inlet and outlet had their tintometer tint number >60 and were found to be highly hazy. According to WHO guidelines, the water supplied must be colourless or its tintometer number must be <5 [16].

g. Odour

All of the water samples examined at the inlet and outlet had their omoscope odour threshold number >4% and were found to be highly odorous. As per WHO guidelines, the water supplied must be odourless [16].

h. Taste

All of the samples surveyed at the inlet and outlet were found to be completely unpleasant to taste. As per WHO guidelines, water must be tasteful [16].

CONCLUSIONS

From the study, it is concluded that the treatment plant is able to reduce turbidity by a great margin, but the values at the outlet are far beyond the limits guided by the WHO. The outlet values average to about 100NTU but the WHO recommends a turbidity of <5NTU at the outlet. The treatment plant doesn't treat TDS at all, but the inlet and outlet values are under the WHO limits. The maximum TDS value at the outlet is 360mg/l which is in the WHO limit of <1000mg/l. The pH values at the outlet are under the WHO guidelines of 6.5-8.5. E-Coliforms are present in every sample of water because there is no provision for biological treatment or disinfection of water. According to WHO guidelines, the water must be free of any biological contaminants. The water gets contaminated in the sedimentation tanks

due to external intrusion. Residual chlorine is not found in any of the samples because the chlorination plant is out of order. According to WHO guidelines, a minimum of 5mg/l of Cl_2 is to be present in water at the outlet. The color, taste and odour of the water at the outlet are always hazy, unpleasant and odorous. According to WHO guidelines, the water at outlet must be colourless, odourless and tasteful.

RECOMMENDATIONS

After reviewing the results of this research and the conclusions, it is recommended that to remove as much turbidity as possible and to treat the water of TDS, coagulation & flocculation must be perfectly carried out or coagulation tanks must be established, the existing sand filters must be brought to working condition, the screens and grit chambers must be introduced, and the capacity of sedimentation tanks must be increased so that the time of retention of water is increased. To stabilize the pH, odour, colour and taste of water, the slow sand filters must be established and brought to working condition so that any of the chemical and biological compounds are removed from the water. To treat the water of biological contaminants, chlorine must be added to the water in the premises of the plant and at the outlet.

It is thus inevitable to follow all the recommendations given here so that the supply of clean, treated freshwater to the public is ensured.

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FLUID FLOW IN AN ASYMMETRIC CHANNEL OF VARIABLE CROSS-SECTION WITH SLIP CONDITION AT THE WALL

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ABSTRACT

This study deals with the effects of slip and phase difference in a steady flow of an incompressible asymmetric rigid channel with permeable walls. It is assumed that the effect of fluid absorption through permeable walls is accounted by prescribing flux as a function of axial distance. The perturbation method is applied to linearize the non-linear governing equations by assuming the ratio of inlet width to wavelength to be small. Effects of the above parameters on the velocity profile, mean pressure drop and wall shear stress are studied in detail and explained graphically.

Keywords: Permeable channel, slip parameter, asymmetry.

1 INTRODUCTION

The study of the flow of viscous fluid in an asymmetric channel of varying cross section with permeable walls is much interested in recent years in view of its numerous applications in many physiological and engineering problems. Fluid flow in renal tubules was studied by many authors. Mathematical modeling of the flow in proximal renal tubule was first studied by Macey [16] where he considered the flow of an incompressible viscous fluid through a circular tube with a linear rate of reabsorption at the wall. Bulk flow in the proximal tubule decays exponentially with the axial distance was calculated by Kelman [5]. Then, Macey [17] used this condition to solve the equations of motion to find the average pressure drop. Marshall *et.al*[7] and Palatt *et al*[12] studied the physical conditions existing at the rigid permeable wall instead of prescribing the flux /radial velocity at the wall.

In all the above studies the researcher considered the renal tubule to be symmetry. But in general, renal tubules may not be symmetric throughout their length. A hydrodynamical aspect of an incompressible viscous fluid in a circular tube of varying cross-section with reabsorption at the wall is studied by Radhakrishnamacharya *et al*[14]. Flow in rigid tubes of slowly varying cross-section with absorbing wall is studied by Peeyush Chandra and Krishna Prasad [13]. Fluid flow through a diverging/converging tube with variable wall permeability was studied by Chaturani and Ranganatha [2].

The concept of slowly varying flow is given by Manton [6] where he obtained an asymptotic series solution for the low Reynolds number flow through an axisymmetric tube, where radius varies slowly in the axial direction.

The effects of slope parameter and reabsorption coefficient on the flow of fluid in a symmetric channel with varying cross section with no-slip velocity at the walls are studied by Muthu and Tesfahun [9].

In all the above studies the researchers have taken the boundary condition at the wall to be a no-slip condition, whereas the no-slip condition is one of the aspects on which the mechanics of the viscous liquids is built. However, there are many situations where this assumption does not hold [15]. Elshahed [8] illustrated the significance of the effect of slip at the wall. Also, the slip would be most useful for certain problems in chemical engineering and other applications ([15],[3],[4],[18],[19]). Fluid flow through the non-uniform channel with permeable wall and slip effect in symmetry channel is studied by [11]. Further, Muthu and Tesfahun [10] discussed the flow through in renal tubule by considering the asymmetric channel of varying cross-section, whereas Waseem et al [20] study the effect of slip on fluid flow in a channel of the slowly varying cross section.

Thus, in this paper, an attempt is made to understand the flow through renal tubule of asymmetry channel of varying cross-section and a slip velocity at the walls of the channel.

2 MATHEMATICAL FORMULATION

Here we consider an incompressible fluid flow through the asymmetric channel with a slowly varying cross-section. The boundaries of the channel wall are taken by Muthu *et al*[10]as

$$\eta_1(x) = d_1 + a_1 \cos\left(\frac{2\pi x}{\lambda}\right) \quad \text{..... upper wall}$$

$$\eta_2(x) = -d_2 - b_1 \cos\left(\frac{2\pi x}{\lambda} + \phi\right) \quad \text{..... lower wall}$$

, where $0 \le x \le \lambda$ (1)

Where d_1 and d_2 are the half width of the channel from the x-axis to $\eta_1(x)$ and $\eta_2(x)$ respectively at the inlet (at x=0), a_1 and b_1 are amplitudes and λ is the wavelength further a_1 , b_1 , d_1 , d_2 , ϕ satisfies the condition

$$a_1^2 + b_1^2 + 2a_1 b_1 \cos(\phi) \le (d_1 + d_2)^2 \quad (2)$$

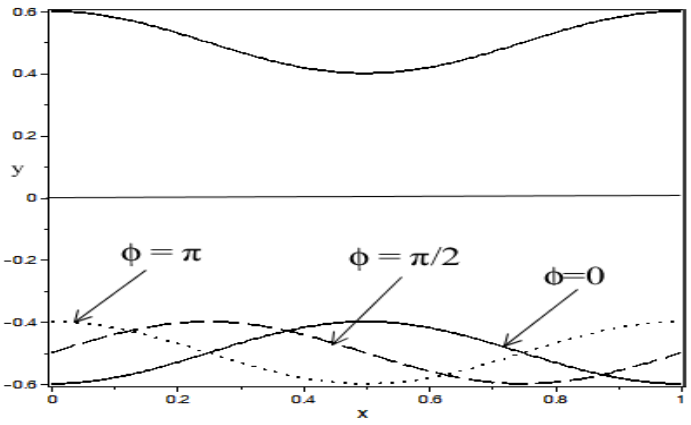


Figure 1. Geometry of the channel

We shall consider the motion of the fluid to be laminar and steady and the channel to be long enough to neglect the initial and end effects. The equations of continuity and momentum are given by

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{3}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{4}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{5}$$

Where u and v are the velocity components along the x and y axes respectively, p is the pressure, ρ is the density of the fluid and $\nu=\frac{\mu}{\rho}$ is kinematic viscosity.

In order to complete the formulation of the problem, the boundary conditions are taken as follows.

(a) The tangential velocity at the wall is not zero. That is,

$$u+\frac{d\eta_1}{dx}v=-\frac{\sqrt{\gamma}}{\beta}\left(\frac{\partial u}{\partial y}+\frac{d\eta_1}{dx}\frac{\partial v}{\partial y}\right) \quad \text{at} \quad y=\eta_1(x) \tag{6}$$

$$u+\frac{d\eta_2}{dx}v=-\frac{\sqrt{\gamma}}{\beta}\left(\frac{\partial u}{\partial y}+\frac{d\eta_2}{dx}\frac{\partial v}{\partial y}\right) \quad \text{at} \quad y=\eta_2(x) \tag{7}$$

Where β is slip parameter and γ is the specific permeability of the porous medium.

(b) The reabsorption has been accounted for by considering the bulk flow as a decreasing function of *x*. That is, the flux across a cross-section is given by

$$Q(x)=\int_{\eta_2(x)}^{\eta_1(x)} u(x,y)\,dy=Q_o\,F(\alpha x) \quad , \tag{8}$$

Where $F(\alpha x)=1$ when $\alpha=0$ and decreases with x, $\alpha\geq 0$ is the reabsorption coefficient and is a constant, and Q_o is the flux across the cross-section at x=0.

The boundary conditions (6) and (7) are well known Beavers and Joseph[1] condition when applied to tangential velocity.

We introduce the stream function ψ such that

$$u=\frac{\partial \psi}{\partial y} \quad , \quad v=-\frac{\partial \psi}{\partial x} \tag{9}$$

And the non-dimensional quantities as

$$x'=\frac{x}{\lambda},\ y'=\frac{y}{d},\ \eta_1'=\frac{\eta_1}{d},\quad \eta_2'=\frac{\eta_2}{d},\ \psi'=\frac{\psi}{Q_o},\ \alpha'=\alpha\lambda,\ p'=\frac{d^2}{\mu Q_o}p$$

Where $d = d_1 + d_2$.

By introducing the above non-dimensional variables the equations (3)—(5) can be written as (the primes are dropped)

$$\left(\delta^2 \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)^2 \psi = \delta \mathrm{R}\left[\frac{\partial \psi}{\partial y}\left(\delta^2 \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\frac{\partial \psi}{\partial x} - \frac{\partial \psi}{\partial x}\left(\delta^2 \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\frac{\partial \psi}{\partial y}\right] \tag{10}$$

Where $\delta = \frac{d}{\lambda}$ and $R = \frac{Q_o}{\nu}$.

Further, the boundary conditions (6—8) becomes

$$\left[\frac{\partial \psi}{\partial y} + A\delta \sin(2\pi x)\frac{\partial \psi}{\partial x}\right] = -\xi\left[\frac{\partial^2 \psi}{\partial y^2} - A\delta \sin(2\pi x)\frac{\partial^2 \psi}{\partial y \partial x}\right] \text{ at } y = \eta_1(x) = \beta_1 + \varepsilon_1 \cos(2\pi x) \tag{11}$$

$$\left[\frac{\partial \psi}{\partial y} - B\delta \sin(2\pi x + \phi)\frac{\partial \psi}{\partial x}\right] = -\xi\left[\frac{\partial^2 \psi}{\partial y^2} - B\delta \sin(2\pi x + \phi)\frac{\partial^2 \psi}{\partial y \partial x}\right] \text{ at } y = \eta_2(x) = \beta_2 + \varepsilon_2 \cos(2\pi x + \phi) \tag{12}$$

$$\psi = \frac{1}{2}F(\alpha x) \text{ at } \quad y = \eta_1(x) = \beta_1 + \varepsilon_1 \cos(2\pi x) \tag{13}$$

$$\psi = -\frac{1}{2}F(\alpha x) \text{ at } y = \eta_2(x) = \beta_2 + \varepsilon_2 \cos(2\pi x + \phi) \tag{14}$$

Where $A = \left(-\frac{2\pi a_1}{\lambda}\right)$, $B = \left(\frac{2\pi b_1}{\lambda}\right)$, $\varepsilon_1 = \frac{a_1}{d}$, $\varepsilon_2 = -\frac{b_1}{d}$, $\beta_1 = \frac{d_1}{d}$, $\beta_2 = -\frac{d_2}{d}$, $\xi = \frac{\sqrt{\gamma}}{\mathrm{d}\beta}$

The parameter R is the Reynolds number and δ is the wavenumber (the ratio of inlet width to the wavelength). ε_1 and ε_2 are amplitude ratios (the ratios of amplitudes a_1 and b_1 to the inlet width respectively) and β_1 and β_2 are ratios of distance from the x-axis to the upper wall and lower wall to the inlet width respectively. In this problem, we consider exponentially decaying bulk flow [6] that is, in equation (8), *F* is taken as

$$F(\alpha x) = e^{-\alpha x} \tag{15}$$

3 METHOD OF SOLUTION

It is observed that the flow is quite complex because of nonlinearity of governing equation and the boundary conditions (10)-(14). Thus to solve equation (10) for velocity components, in the present analysis, we assume the wave number δ □ (long wavelength approximation). We shall seek a solution for stream function $\psi(x, y)$ in the form of a power series in terms of δ, as

$$\psi(x, y) = \psi_0(x, y) + \delta\psi_1(x, y) + .. \tag{16}$$

Substituting equation (16) in equations (10)-(14), and equating the coefficients of like powers of δ, we get the following sets of equations for $\psi_0(x, y)$, $\psi_1(x, y)$,...

Zeroth Order System

$$\frac{\partial^4 \psi_0}{\partial y^4} = 0 \tag{17}$$

The corresponding boundary conditions are:

$$\frac{\partial \psi_0}{\partial y} = -\xi \frac{\partial^2 \psi_0}{\partial y^2} \text{ at } y = \eta_1(x) \text{ and } y = \eta_2(x) \tag{18}$$

$$\psi_o = F(\alpha x) = \frac{1}{2} e^{-\alpha x} \quad at\ y = \eta_1(x) \tag{19}$$

$$\psi_o = -F(\alpha x) = -\frac{1}{2} e^{-\alpha x} \quad at\ y = \eta_2(x) \tag{20}$$

First Order System

$$\frac{\partial^4 \psi_1}{\partial y^4} = \mathrm{R}\left[\frac{\partial \psi_0}{\partial y} \frac{\partial^3 \psi_0}{\partial y^2 \partial x} - \frac{\partial \psi_0}{\partial x} \frac{\partial^3 \psi_0}{\partial y^3} \right] \tag{21}$$

The corresponding boundary conditions are:

$$\frac{\partial \psi_1}{\partial y} = A \sin(2\pi x) \frac{\partial \psi_0}{\partial x} - \xi \left[\frac{\partial^2 \psi_1}{\partial y^2} - A \sin(2\pi x) \frac{\partial^2 \psi_0}{\partial y \partial x} \right] \quad \text{at } y = \eta_1(x) \tag{22}$$

$$\frac{\partial \psi_1}{\partial y} = B \sin(2\pi x + \phi) \frac{\partial \psi_0}{\partial x} - \xi \left[\frac{\partial^2 \psi_1}{\partial y^2} - B \sin(2\pi x + \phi) \frac{\partial^2 \psi_0}{\partial y \partial x} \right] \quad \text{at } y = \eta_2(x) \tag{23}$$

$$\psi_0 = 0 \text{ at } y = \eta_1(x) \quad \text{and} \quad y = \eta_2(x) \tag{24}$$

Similar expressions can be written for higher orders of δ. However, since we are looking for an approximate analytical solution for the problem, we consider up to the order of δ^1 equations.

The solution of equation (17) along with the corresponding boundary conditions (18-20) as

$$\psi_0 = \frac{1}{2}\left[A_1(x) y^3 + A_2(x) y^2 + A_3(x) y + A_4(x) \right] \tag{25}$$

Following the similar procedure as in equation (25) the solution of equation (21) along with boundary conditions (22-24) is

$$\psi_1 = R\left[\frac{1}{840} A_5(x) y^7 + \frac{1}{360} A_6(x) y^6 + \frac{1}{120} A_7(x) y^5 + \frac{1}{24} A_8(x) y^4 \right]$$
$$+ \frac{1}{6} A_9(x) y^3 + \frac{1}{2} A_{10}(x) y^2 + A_{11}(x) y + A_{12}(x) \tag{26}$$

By substituting the value of ψ_0 and ψ_1 in equation (16), we get

$$\psi = \frac{1}{2}\left[A_1(x) y^3 + A_2(x) y^2 + A_3(x) y + A_4(x) \right]$$
$$+ \delta \left[R\left(\frac{1}{840} A_5(x) y^7 + \frac{1}{360} A_6(x) y^6 + \frac{1}{120} A_7(x) y^5 + \frac{1}{24} A_8(x) y^4 \right) \right.$$

$$+\frac{1}{6}A_9(x)y^3+\frac{1}{2}A_{10}(x)y^2+A_{11}(x)y+A_{12}(x)\Bigg] \tag{27}$$

Now, the nondimensional pressure $p(x,y)$ can be obtained by using equations (27), (9) and (4), and it is given as

$$p(x,y)=\delta\frac{\partial u}{\partial x}+\frac{1}{\delta}\int\frac{\partial^2 u}{\partial y^2}dx-R\left(\int u\frac{\partial u}{\partial x}dx+\int v\frac{\partial u}{\partial y}dx\right) \tag{28}$$

The mean pressure is given as

$$\overline{p}(x)=\frac{1}{\eta_1(x)-\eta_2(x)}\int_{\eta_2(x)}^{\eta_1(x)}p(x,y)\,dy \tag{29}$$

Further, the mean pressure drop between $x=0$ and $x=x_0$ is

$$\Delta\overline{p}(x_0)=\overline{p}(0)-\overline{p}(x_0) \tag{30}$$

The wall shear stress $\tau_w(x)$ is defined as

$$\tau_w(x)=\frac{\left(\sigma_{yy}-\sigma_{xx}\right)\frac{dy}{dx}+\sigma_{xy}\left[1-\left(\frac{dy}{dx}\right)^2\right]}{1+\left(\frac{dy}{dx}\right)^2} \qquad \text{at } y=\eta_1(x) \text{ and } y=\eta_1(x) \tag{31}$$

Where $\sigma_{xx}=2\mu\frac{\partial u}{\partial x}$, $\sigma_{yy}=2\mu\frac{\partial v}{\partial y}$, and $\sigma_{xy}=\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)$

Using the non-dimensional quantity $\tau'_{w_1}=\frac{d^2}{\mu Q_0}\tau_{w_1}$ and $\tau'_{w_2}=\frac{d^2}{\mu Q_0}\tau_{w_2}$, the wall shear stress τ_{w_1} and τ_{w_2} (after dropping the prime) can be written as

$$\tau_{w_1}=\frac{2\delta^2\left(\frac{\partial v}{\partial y}-\frac{\partial u}{\partial x}\right)\frac{d\eta_1}{dx}+\left(\frac{\partial u}{\partial y}+\delta^2\frac{\partial v}{\partial x}\right)\left[1-\delta^2\left(\frac{d\eta_1}{dx}\right)^2\right]}{1+\delta^2\left(\frac{d\eta_1}{dx}\right)^2} \tag{32}$$

$$\tau_{w_2}=\frac{2\delta^2\left(\frac{\partial v}{\partial y}-\frac{\partial u}{\partial x}\right)\frac{d\eta_2}{dx}+\left(\frac{\partial u}{\partial y}+\delta^2\frac{\partial v}{\partial x}\right)\left[1-\delta^2\left(\frac{d\eta_2}{dx}\right)^2\right]}{1+\delta^2\left(\frac{d\eta_2}{dx}\right)^2} \tag{33}$$

It may be noted that in equation (28), the integrals are difficult to evaluate analytically to get closed form expression for $p(x,y)$. Therefore, they are calculated by numerical integration.

4 RESULTS AND DISCUSSION

The purpose of the present discussion is to analyze the behavior of a steady incompressible fluid flow in an asymmetric channel of slowly varying cross-section with absorbing wall by considering a slip velocity at the walls.

It may be noted that ϕ characterized the phase difference which varies in the range $0 \le \phi \le \pi$. Here $\phi = 0$ represents symmetric channel. $\phi = \pi$ represents the asymmetric channel with waves are in phase. α and ξ represents reabsorption coefficient and slip at the channel wall, respectively. It is observed that in the absence of slip i.e., $\xi \to 0$, our results are in tune with those of Muthu and Tesfahun[10].

We discuss the effect of these parameters on the transverse velocity $v(x, y)$, mean pressure drop $(\Delta \bar{p})$, and wall shear stress (τ_w). The following parameters are fixed as A=-0.0628, B=0.0628, $\beta_1 = 0.5, \beta_2 = -0.5, \varepsilon_1 = 0.1, \varepsilon_2 = -0.1, \delta = 0.1$ in our numerical calculation. For low Reynolds number flow, we have taken $R = 1.0$. To see the effect of ξ we have taken ξ=$0, 0.15$ and 0.4.

The Transverse velocity v:

The transverse velocity $v(x, y)$ which is obtained from equations (9) and (27) Here we have discussed the effects of the phase difference (ϕ), in the presence of non-zero slip coefficient (ξ) on the transverse velocity by taking the behavior at a different cross-section of the channel. We have taken $x = 0.1, 0.5, 0.9$ and $\phi = 0, \frac{\pi}{2}, \pi$.

Figure 2(a) displays the effect of (ϕ) on *v* at *x*=0.1 and ξ=0.0. It may be observed that as (ϕ) increases from 0 to π , the magnitude of *v* decreases. It may be remarked that the reabsorption value at the wall is fixed at *x*=0.1 and when (ϕ) increases, the cross-sectional area is reduced. This results in lesser *v* values. Now, if ξ=0.15 similar effect is observed as above. When (ϕ) varies from 0 to π mixed trends is observed in velocity.

If ξ=0.4 the velocity decreases when ϕ varies from 0 to π . But comparing with no slip (ξ=0.0) case velocity increases in quantity. This may be due to the effect of the slip (see figures 2(b), 2(c)).

Figure 3(a) displays the effect of ϕ on *v* at *x*=0.5 with ξ=0.0. It may be noted that as ϕ increases the magnitude of *v* has mixed trends, due to the variation of the cross-section of the channel at *x*=0.5.

If ξ=0.15 and ξ=0.4, similar mixed trends is observed on *v*, due to the effect of slip (see figures 3(b), 3(c)).Figures 4(a)-4(c) display the effect of ϕ on *v* when *x*=0.9 for ξ=0.0, 0.15 and 0.4. It is observed that as ϕ increases the magnitude of *v* has a mixed trend.

Mean Pressure drop

The value of the mean pressure drop (29) over the length of the channel is calculated from different values of ϕ and ξ. Figure 5(a) represents the effect of ϕ when ξ=0.0. It is observed that as the width of channel contracts, the mean pressure drop increases. Particularly, at the entrance of the channel, the mean pressure drop for the asymmetrical channel is more than the symmetrical channel.

It can be understood from figure 5(a) for $\phi = 0, \frac{\pi}{2}, \pi$. However, due to contraction in the middle of the channel, the reverse is true at the end of the channel.

When ξ=0.15, a similar trend as mentioned above is observed, with a quality difference (see fig.5 (b)).

As ξ=0.4, the trend is reversed, this shows the effect of slip combined with asymmetry nature of the channel (fig. 5(c)).

Magnitude of wall shear stress

The effects of ϕ and ξ on the magnitude of the wall shear stress ($|\tau_{w_1}|$ and $|\tau_{w_2}|$) are presented in figures 6 and 7 respectively.

It may be noted from figures 6(a) to 6(b), and 7(a) to 7(b) that the upper wall and lower on shear stress (in magnitude) increases as the channel changed from symmetry to asymmetry and no-slip to slip conditions, except in the middle of the channel where there is more contraction.

This indicates that as the width of the channel decreases due to asymmetry nature of walls, ($|\tau_{w_1}|$ and $|\tau_{w_2}|$) increases. But when ξ=0.4, the nature of the curve is oscillatory [See fig. 6(c) and 7 (c)].

5 CONCLUSIONS

The main contribution of this study is to see the effect of the phase difference in the presence of slip at the walls on the flow of incompressible fluid in an asymmetric channel of the slowly varying cross-section. The mathematical problem is solved using a regular perturbation method assuming the ratio of inlet width to wavelength is small. We observe the following observation in the present study.

(i) As phase difference increases the magnitude of velocity decreases.
(ii) As the channel changes from symmetric to asymmetric the mean pressure drop increases.
(iii) The wall shear stress increases as the channel changes from symmetry to asymmetry and no slip to slip.

APPENDIX – IMPORTANT FORMULAS AND GRAPHS

$$A_1(x) = \frac{4e^{-\alpha x}}{\eta_2^3-\eta_1^3+3\eta_1^2\eta_2-3\eta_2^2\eta_1-12\xi^2\eta_2+12\xi^2\eta_1}, \quad A_2(x) = \frac{-6\left(\eta_1+2\xi+\eta_2\right)e^{-\alpha x}}{\eta_2^3-\eta_1^3+3\eta_1^2\eta_2-3\eta_2^2\eta_1-12\xi^2\eta_2+12\xi^2\eta_1}$$

$$A_3(x) = \frac{12\left(\xi\eta_1+2\xi^2+\eta_1\eta_2+\xi\eta_2\right)e^{-\alpha x}}{\eta_2^3-\eta_1^3+3\eta_1^2\eta_2-3\eta_2^2\eta_1-12\xi^2\eta_2+12\xi^2\eta_1}$$

$$A_4(x) = \frac{-e^{-\alpha x}\left(-\eta_2^3-\eta_1^3+3\eta_1^2\eta_2+3\eta_2^2\eta_1+12\xi\eta_2+12\xi\eta_1+12\xi\eta_1\eta_2\right)}{\eta_2^3-\eta_1^3+3\eta_1^2\eta_2-3\eta_2^2\eta_1-12\xi^2\eta_2+12\xi^2\eta_1}$$

$$A_5(x)=12A_1(x)\left(\frac{dA_1}{dx}\right),\ A_6(x)=12A_2(x)\left(\frac{dA_1}{dx}\right)$$

$$A_7(x)=4A_2(x)\left(\frac{dA_2}{dx}\right)+6A_3(x)\left(\frac{dA_1}{dx}\right)-6A_1(x)\left(\frac{dA_3}{dx}\right),$$

$$A_8(x)=2A_3(x)\left(\frac{dA_2}{dx}\right)-6A_1(x)\left(\frac{dA_4}{dx}\right)$$

$$A_9(x)=\frac{1}{420(\eta_1-\eta_2)\left(12\xi^2-(\eta_1-\eta_2)^2\right)}\Big[-7560B(2\xi+\eta_1-\eta_2)A_{13}\sin(2\pi x+\phi)$$

$$+7560(2\xi-\eta_1+\eta_2)A_{14}\sin(2\pi x)$$

$$-3024R(\eta_1-\eta_2)\Big\{\xi\Big(A_1A_{15}+\left(10(\eta_1+\eta_2)\left(\eta_1^2+\eta_2^2\right)\xi-5\eta_2^4-5\eta_1^4\right)\frac{A_2}{6}$$

$$+\frac{5}{6}\left(2\xi\left(\eta_2^2+\eta_1^2+\eta_1\eta_2\right)-\eta_1^3-\eta_2^3\right)A_3\Big)\frac{dA_1}{dx}$$

$$+\frac{10\xi A_{17}}{9}\frac{dA_2}{dx}-\frac{5\xi A_1}{6}\left(2\xi\left(\eta_2^2+\eta_1^2+\eta_1\eta_2\right)-\eta_1^3-\eta_2^3\right)\frac{dA_3}{dx}$$

$$-\frac{5\xi A_1}{2}\left(2\xi(\eta_1+\eta_2)-\eta_1^2-\eta_2^2\right)\frac{dA_4}{dx}+A_5A_{16}$$

$$+\left(\left(\eta_1^4+\eta_2^4+\eta_1^3\eta_2+\eta_2^3\eta_1+\eta_1^2\eta_2^2\right)\frac{\xi}{36}-\frac{1}{216}(\eta_1-\eta_2)^2(\eta_1+\eta_2)\left(2\eta_2^2+2\eta_1^2+\eta_1\eta_2\right)\right)A_5$$

$$+\left(\frac{5}{72}(\eta_1+\eta_2)\left(\eta_1^2+\eta_2^2\right)\xi-\frac{1}{144}(\eta_1-\eta_2)^2\left(3\eta_2^2+3\eta_1^2+4\eta_1\eta_2\right)\right)A_7$$

$$+\frac{5}{72}\left(4\xi\left(\eta_2^2+\eta_1^2+\eta_1\eta_2\right)-(\eta_1+\eta_2)(\eta_1-\eta_2)^2\right)A_8\Big\}\Big]$$

$$A_{13}(x)=\eta_2^2\left(\frac{1}{3}\eta_2+\xi\right)\frac{dA_1}{dx}+\frac{2}{3}\eta_2\left(\frac{1}{2}\eta_2+\xi\right)\frac{dA_2}{dx}+\frac{1}{3}(\eta_2+\xi)\frac{dA_3}{dx}+\frac{1}{3}\frac{dA_4}{dx}$$

$$A_{14}(x)=\eta_1^2\left(\frac{1}{3}\eta_1+\xi\right)\frac{dA_1}{dx}+\frac{2}{3}\eta_1\left(\frac{1}{2}\eta_1+\xi\right)\frac{dA_2}{dx}+\frac{1}{3}(\eta_1+\xi)\frac{dA_3}{dx}+\frac{1}{3}\frac{dA_4}{dx}$$

$$A_{15}(x)=\left(\eta_1^4+\eta_2^4+\eta_1^2\eta_2^2+\eta_1^3\eta_2+\eta_1\eta_2^3\right)\xi-\frac{1}{2}\left(\eta_1^5+\eta_2^5\right)$$

$$A_{16}(x)=\frac{1}{72}(\eta_1+\eta_2)\left(\eta_2^2+\eta_1^2+\eta_1\eta_2\right)\left(\eta_1^2+\eta_2^2-\eta_1\eta_2\right)\xi$$

$$-\frac{5}{1008}\left(\eta_1^4+\frac{8}{5}\eta_1^3\eta_2+\frac{9}{5}\eta_2^2\eta_1^2+\frac{8}{5}\eta_2^3\eta_1+\eta_2^4\right)\left(\eta_1^2-\eta_2^2\right)^2$$

$$A_{17}(x)=\left(\left(\eta_1^2+\eta_2^2+\eta_1\eta_2\right)\xi-\frac{1}{2}\eta_1^3-\frac{1}{2}\eta_2^2\right)A_2(x)-3A_3(x)$$

$$A_{10}(x)=\frac{1}{420}\frac{1}{(\eta_1-\eta_2)\left(-\eta_1^2+2\eta_2\eta_1-\eta_2^2+12\xi^2\right)}\Big[15120B\left\{\frac{1}{3}\eta_1^2+\left(-\frac{1}{6}\eta_2+\xi\right)\eta_1-\frac{1}{6}\eta_1^2\right\}A_{18}\sin(2\pi x+\phi)$$

$$-15120\left(-\frac{1}{6}\eta_1^2-\frac{1}{6}\eta_1\eta_2+\eta_2\left(\frac{1}{3}\eta_2+\xi\right)\right)AA_{19}\sin(2\pi x)$$

$$-15120R(\eta_1-\eta_2)\left\{-\frac{1}{5}\xi\left(A_{21}A_1+A_{27}A_2+\frac{5}{3}A_3A_{28}\right)\frac{dA_1}{dx}+\frac{2}{3}\xi\left(A_3\left(\xi+\frac{\eta_1}{2}+\frac{\eta_2}{2}\right)-\frac{A_{28}A_2}{3}\right)\frac{dA_2}{dx}\right.$$

$$+A_1\xi\left(-\frac{1}{6}\eta_1^3-\frac{1}{3}\eta_2\eta_1^2+\eta_2\left(-\frac{1}{3}\eta_2+\xi\right)\eta_1-\frac{1}{6}\eta_2^3\right)\frac{dA_4}{dx}$$

$$+\frac{1}{3}A_1A_{28}\xi\frac{dA_3}{dx}+\frac{1}{3780}A_5\eta_1^7+\left(-\frac{1}{2520}A_5\xi+\frac{1}{2160}A_6+\frac{1}{1890}\eta_2A_5\right)\eta_1^6$$

$$\left.-\frac{1}{5}A_{20}\eta_1^5-\frac{1}{5}A_{22}\eta_1^4-\frac{1}{5}A_{23}\eta_1^3-\frac{1}{315}A_{24}\eta_2\eta_1^2-\frac{1}{315}A_{25}\eta_1\eta_2^2-\frac{1}{2520}A_{26}\eta_2^3\right\}\Bigg]$$

$$A_{18}(x)=\frac{1}{3}\left[\left(\eta_2^3+3\eta_2^2\xi\right)\frac{dA_1}{dx}+\left(\eta_2^2+2\eta_2\xi\right)\frac{dA_2}{dx}+\left(\eta_2+\xi\right)\frac{dA_3}{dx}+\frac{dA_4}{dx}\right]$$

$$A_{19}(x)=\frac{1}{3}\left[\left(\eta_1^3+3\eta_2^2\xi\right)\frac{dA_1}{dx}+\left(\eta_1^2+2\eta_1\xi\right)\frac{dA_2}{dx}+\left(\eta_1+\xi\right)\frac{dA_3}{dx}+\frac{dA_4}{dx}\right]$$

$$A_{20}(x)=\frac{1}{1512}\left[\left(24\xi A_5-7A_6\right)\eta_2+7\xi A_6-7A_7+3A_5\eta_2^2\right]$$

$$A_{21}(x)=-\frac{\eta_2^6}{6}-+\frac{\eta_2}{6}\left(-2\eta_1^5+6\xi\eta_1^4\right)-\frac{\eta_1^6}{6}-\frac{\eta_2^5\eta_1}{3}+\eta_2^4\eta_1\xi+\eta_1^2\eta_2^3\xi+\eta_1^3\eta_2^2\xi$$

$$A_{22}(x)=\frac{A_5\eta_2^3}{504}+\left(\frac{\xi A_5}{63}+\frac{A_6}{216}\right)\eta_2^2+\left(-\frac{A_7}{108}+\frac{7\xi A_6}{216}\right)\eta_2+\frac{\xi A_7}{72}-\frac{5A_8}{432}$$

$$A_{23}(x)=\frac{A_5\eta_2^4}{504}+\frac{1}{1512}\left(24\xi A_5+7A_6\right)\eta_2^3+\frac{1}{1512}\left(49\xi A_6+21A_7\right)\eta_2^2+\frac{1}{1512}\left(126\xi A_7-35A_8\right)\eta_2+\frac{5}{72}\xi A_8$$

$$A_{24}(x)=\frac{A_5\eta_2^4}{8}+\frac{1}{24}\left(24\xi A_5+7A_6\right)\eta_2^3+\frac{1}{24}\left(49\xi A_6+21A_7\right)\eta_2^2+\frac{1}{24}\left(126\xi A_7+105A_8\right)\eta_2+\frac{175}{8}\xi A_8$$

$$A_{25}(x)=-\frac{A_5\eta_2^4}{6}+\frac{1}{24}\left(24\xi A_5-7A_6\right)\eta_2^3+\frac{1}{24}\left(49\xi A_6-14A_7\right)\eta_2^2+\frac{1}{24}\left(126\xi A_7-35A_8\right)\eta_2+\frac{175}{8}\xi A_8$$

$$A_{26}(x)=-\frac{2A_5\eta_2^4}{3}+\frac{1}{6}\left(6\xi A_5-7A_6\right)\eta_2^3+\frac{1}{6}\left(14\xi A_6-14A_7\right)\eta_2^2+\frac{1}{6}\left(42\xi A_7-35A_8\right)\eta_2+35\xi A_8$$

$$A_{27}(x)=-\frac{5\eta_2^4}{18}-\frac{5}{9}\eta_2^4\eta_1+\frac{5}{3}\eta_2^3\eta_1\xi+\frac{5}{3}\eta_1^2\eta_2^2\xi+\frac{1}{18}\left(-10\eta_1^4+30\eta_1^3\xi\right)\eta_2-\frac{5}{18}\eta_1^5$$

$$A_{28}(x)=-\frac{1}{6}\eta_2^4-\frac{1}{3}\eta_2^3\eta_1+\eta_2^2\eta_1\xi+\frac{1}{6}\left(-2\eta_1^3+6\eta_1^2\xi\right)\eta_2-\frac{1}{6}\eta_1^4$$

$$A_{11}(x)=\frac{1}{840}\frac{12}{\left(\eta_1-\eta_2\right)\left(-\eta_1^2+2\eta_1\eta_2-\eta_2^2+\xi^2\right)}$$

$$\Big[-10080BB_1B_2\sin\left(2\pi x+\phi\right)-5040AB_{10}B_3\sin\left(2\pi x\right)$$

$$+1008R\left(\eta_1-\eta_2\right)\left\{B_{12}\xi\frac{dA_1}{dx}+\frac{10}{7}B_7\xi\frac{dA_2}{dx}-\frac{5}{3}A_1\xi B_8\frac{dA_3}{dx}\right.$$

$$-5A_1\xi B_9\frac{dA_4}{dx}+A_5\left(\left(\frac{1}{126}\xi+\frac{1}{126}\eta_2\right)\eta_1^7+\left(-\frac{1}{84}\xi^2+\frac{1}{1008}\eta_2^2-\frac{13}{504}\xi\eta_2\right)\eta_1^6\right.$$

$$-\frac{1}{84}\eta_2\left(\xi^2+\frac{1}{2}\eta_2^2+\frac{9}{2}\xi\eta_2\right)\eta_1^5-\frac{1}{84}\eta_2^2\left(\xi^2+\frac{1}{2}\eta_2^2+\frac{9}{2}\xi\eta_2\right)\eta_1^4$$

$$-\frac{1}{84}\eta_2^3\left(\xi^2+\frac{1}{2}\eta_2^2+\frac{9}{2}\xi\eta_2\right)\eta_1^3-\frac{1}{84}\eta_2^4\left(\xi^2-\frac{1}{12}\eta_2^2+\frac{9}{2}\xi\eta_2\right)\eta_1^2$$

$$-\frac{1}{84}\eta_2^5\left(\xi^2-\frac{2}{3}\eta_2^2+\frac{13}{6}\xi\eta_2\right)\eta_1-\frac{1}{84}\eta_2^6\left(\xi-\frac{2}{3}\eta_2\right)\xi\Bigg)$$

$$+A_6\Bigg(\left(\frac{1}{72}\xi+\frac{1}{72}\eta_2\right)\eta_1^6-\frac{1}{36}\xi(2\eta_2+\xi)\eta_1^5-\frac{1}{36}\left(\frac{1}{2}\eta_2^2+4\xi\eta_2+\xi^2\right)\eta_2\eta_1^4$$

$$-\frac{1}{36}\left(\frac{1}{2}\eta_2^2+4\xi\eta_2+\xi^2\right)\eta_2^2\eta_1^3-\frac{1}{36}\xi\eta_2^3(4\eta_2+\xi)\eta_1^2$$

$$-\frac{1}{36}\left(2\eta_2\xi-\frac{1}{2}\eta_2^2+\xi^2\right)\eta_2^4\eta_1-\frac{1}{36}\left(-\frac{1}{2}\eta_2+\xi\right)\xi\eta_2^5\Bigg)+B_{11}A_7-\frac{5}{12}B_4A_8\Bigg\}\Bigg]$$

$$B_1(x)=\eta_2^2\left(\frac{1}{3}\eta_2+\xi\right)\frac{dA_1}{dx}+\frac{2}{3}\eta_2\left(\frac{1}{2}\eta_2+\xi\right)\frac{dA_2}{dx}+\left(\frac{1}{3}\eta_2+\frac{1}{3}\xi\right)\frac{dA_3}{dx}+\frac{1}{3}\frac{dA_4}{dx}$$

$$B_2(x)=\frac{1}{4}\eta_1^3+\left(\frac{1}{4}\eta_2+\xi\right)\eta_1^2+\left(-\frac{1}{2}\eta_2+\xi\right)\eta_1\eta_2-\frac{1}{2}\eta_2^2\xi$$

$$B_3(x)=\eta_1^2\left(\frac{1}{3}\eta_2+\xi\right)\frac{dA_1}{dx}+\frac{2}{3}\eta_1\left(\frac{1}{2}\eta_1+\xi\right)\frac{dA_2}{dx}+\left(\frac{1}{3}\eta_1+\frac{1}{3}\xi\right)\frac{dA_3}{dx}+\frac{1}{3}\frac{dA_4}{dx}$$

$$B_4(x)=\eta_1^4\left(-\frac{1}{6}\eta_2-\frac{1}{6}\xi\right)+\eta_1^3\left(\xi^2+\frac{5}{3}\xi\eta_2+\frac{1}{6}\eta_2^2\right)+\eta_2\eta_1^2\left(3\xi\eta_2+\frac{1}{6}\eta_2^2+\xi^2\right)$$
$$+\eta_1\eta_2^2\left(\frac{5}{3}\xi\eta_2-\frac{1}{6}\eta_2^2+\xi^2\right)+\xi\eta_2^3\left(-\frac{1}{6}\eta_2+\xi\right)$$

$$B_5(x)=(\eta_2+\xi)\eta_1^6-\left(-\frac{1}{2}\eta_2+\xi\right)\eta_2\eta_1^5-3\eta_2^2\eta_1^4\xi-3\eta_1^3\eta_2^3\xi-3\left(-\frac{1}{6}\eta_2+\xi\right)\eta_2^4\eta_1^2-\eta_2^5(-\eta_2+\xi)\eta_1+\eta_2^6\xi$$

$$B_6(x)=\left(\frac{5}{3}\xi+\frac{5}{3}\eta_2\right)\eta_1^5-\frac{5}{3}\left(-\frac{1}{2}\eta_2+\xi\right)\eta_2\eta_1^4-5\eta_2^2\eta_1^3\xi-5\left(-\frac{1}{6}\eta_2+\xi\right)\eta_1^2\eta_2^3-\frac{5}{3}\eta_2^4(-\eta_2+\xi)\eta_1+\frac{5}{3}\eta_2^5\xi$$

$$B_7(x)=\Bigg((\eta_2+\xi)\eta_1^4-\left(-\frac{1}{2}\eta_2+\xi\right)\eta_2\eta_1^3-3\left(-\frac{1}{6}\eta_2+\xi\right)\eta_2^2\eta_1^2-\eta_2^3(-\eta_2+\xi)\eta_1+\xi\eta_2^4\Bigg)A_2$$
$$+9A_3\left(\frac{1}{6}\eta_1^2+\left(\xi+\frac{2}{3}\eta_2\right)\eta_1+\left(\frac{1}{6}\eta_2+\xi\right)\eta_2\right)$$

$$B_8(x)=(\eta_2+\xi)\eta_1^4-\left(-\frac{1}{2}\eta_2+\xi\right)\eta_2\eta_1^3-3\left(-\frac{1}{6}\eta_2+\xi\right)\eta_2^2\eta_1^2-\eta_2^3(-\eta_2+\xi)\eta_1+\xi\eta_2^4$$

$$B_9(x)=(\eta_2+\xi)\eta_1^3-(-\eta_2+\xi)\eta_2\eta_1^2-(-\eta_2+\xi)\eta_2^2\eta_1-\eta_2^3\xi$$

$$B_{10}(x)=(\eta_2+\xi)\eta_1^2-2\left(\frac{1}{4}\eta_2+\xi\right)\eta_2\eta_1-2\left(\frac{1}{4}\eta_2+\xi\right)\eta_2^2$$

$$B_{11}(x)=\frac{1}{36}(\eta_2+\xi)\eta_1^5-\left(-\frac{11}{72}\xi\eta_2-\frac{1}{144}\eta_2^2-\frac{1}{12}\xi^2\right)\eta_1^4-\frac{1}{12}\left(\frac{7}{2}\xi\eta_2+\xi^2+\frac{1}{2}\eta_2^2\right)\eta_1^3\eta_2$$
$$-\frac{1}{12}\eta_2^2\eta_1^2\left(\frac{1}{12}\eta_2^2+\frac{7}{2}\xi\eta_2+\xi^2\right)-\frac{1}{12}(2\eta_2+\xi)\left(-\frac{1}{6}\eta_2+\xi\right)\eta_2^3\eta_1-\frac{1}{12}\left(-\frac{1}{3}\eta_2+\xi\right)\xi\eta_2^4$$

$$B_{12}(x)=B_5A_1+B_6A_2+\frac{5}{3}\Bigg[(\eta_2+\xi)\eta_1^4-\left(-\frac{1}{2}\eta_2+\xi\right)\eta_2\eta_1^3-3\left(-\frac{1}{6}\eta_2+\xi\right)\eta_2^2\eta_1^2-\eta_2^3(-\eta_2+\xi)\eta_1+\xi\eta_2^4\Bigg]A_3$$

$$C_1(x)=\eta_2^2\left(\frac{1}{3}\eta_2+\xi\right)\frac{dA_5}{dx}+\frac{2}{3}\eta_2\left(\frac{1}{2}\eta_2+\xi\right)\frac{dA_6}{dx}+\left(\frac{1}{3}\eta_2+\frac{1}{3}\xi\right)\frac{dA_7}{dx}+\frac{1}{3}\frac{dA_8}{dx}$$

$$C_2(x)=\eta_1^2\left(\frac{1}{3}\eta_1+\xi\right)\frac{dA_5}{dx}+\frac{2}{3}\eta_1\left(\frac{1}{2}\eta_1+\xi\right)\frac{dA_6}{dx}+\left(\frac{1}{3}\eta_1+\frac{1}{3}\xi\right)\frac{dA_7}{dx}+\frac{1}{3}\frac{dA_8}{dx}$$

$$C_3(x)=-\frac{2}{5}A_5\eta_2^4+\left(\xi A_5-\frac{7}{6}A_6\right)\eta_2^3+\left(\frac{7}{3}\xi A_6-\frac{7}{3}A_7\right)\eta_2^2+\left(7\xi A_7-\frac{35}{6}A_8\right)\eta_2+35\xi A_8$$

$$C_4(x)=\left(\left(\xi+\frac{1}{2}\eta_2\right)\eta_1^3-\xi\eta_2\eta_1^2-\left(-\frac{1}{2}\eta_2+\xi\right)\eta_1\eta_2^2+\xi\eta_2^3\right)A_6+9\left(\frac{1}{6}\eta_2+\xi+\frac{1}{6}\eta_1\right)A_7$$

$$C_5(x)=\left(\xi+\frac{1}{2}\eta_2\right)\eta_1^5-\xi\eta_2\eta_1^4-\xi\eta_2^2\eta_1^3-\xi\eta_1^2\eta_2^3-\eta_2^4\left(\xi+\frac{1}{2}\eta_2\right)\eta_1+\xi\eta_2^5$$

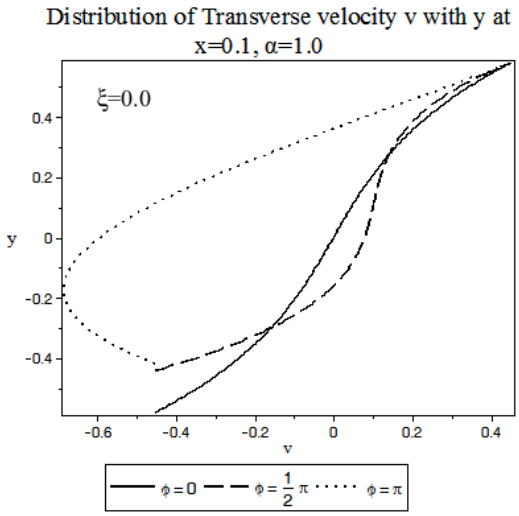
$$C_6(x)=\left(\xi+\frac{1}{2}\eta_2\right)\eta_1^3-\xi\eta_2\eta_1^2-\eta_2^2\left(\xi-\frac{1}{2}\eta_2\right)\eta_1+\xi\eta_2^3$$

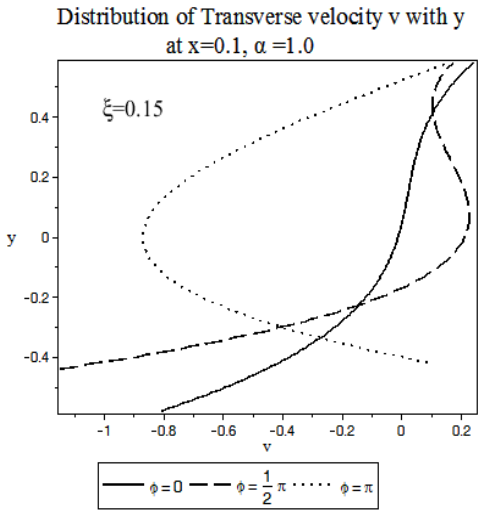
$$C_7(x)=-\frac{1}{7}A_5\eta_2^4+\left(\xi A_5-\frac{1}{4}A_6\right)\eta_2^3+\eta_2^2\left(2\xi A_6-\frac{1}{2}A_7\right)+\left(5\xi A_7-\frac{5}{4}A_8\right)\eta_2+20\xi A_8$$

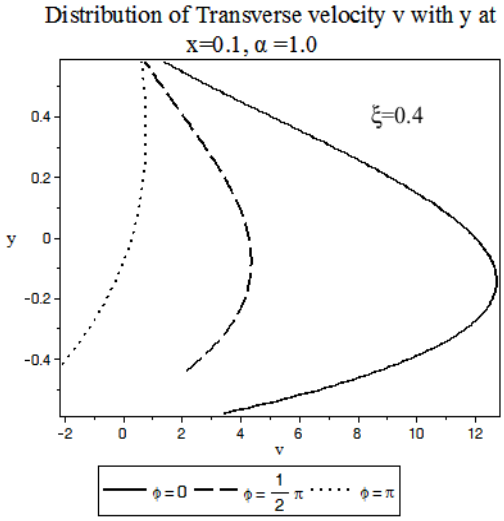
$$C_8(x)=\left[\left(\xi+\frac{1}{2}\eta_2\right)\eta_1^5-\xi\eta_2\eta_1^4-\xi\eta_2^2\eta_1^3-\xi\eta_1^2\eta_2^3-\eta_2^4\left(\xi-\frac{1}{2}\eta_2\right)\eta_1+\xi\eta_2^5\right]A_5$$

$$+\left[\left(\frac{5}{3}\xi+\frac{5}{6}\eta_2\right)+\eta_1^4-\frac{5}{3}\xi\eta_1^3\eta_2-\frac{5}{3}\xi\eta_1^2\eta_2^2-\frac{5}{3}\eta_2^3\left(-\frac{1}{2}\eta_2+\xi\right)\eta_1+\frac{5}{3}\xi\eta_2^4\right]A_6$$

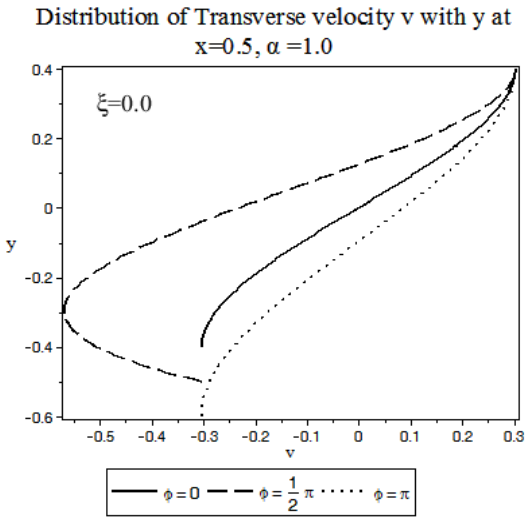
$$+\frac{5}{3}\left[\left(\xi+\frac{1}{2}\eta_2\right)\eta_1^3-\xi\eta_1^2\eta_2-\eta_2^2\left(-\frac{1}{2}\eta_2+\xi\right)\eta_1+\xi\eta_2^3\right]A_7$$

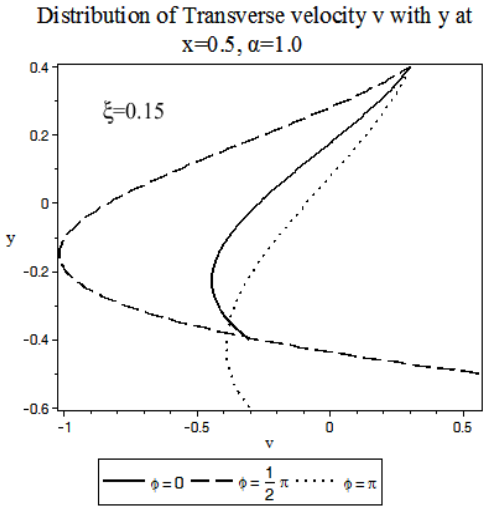


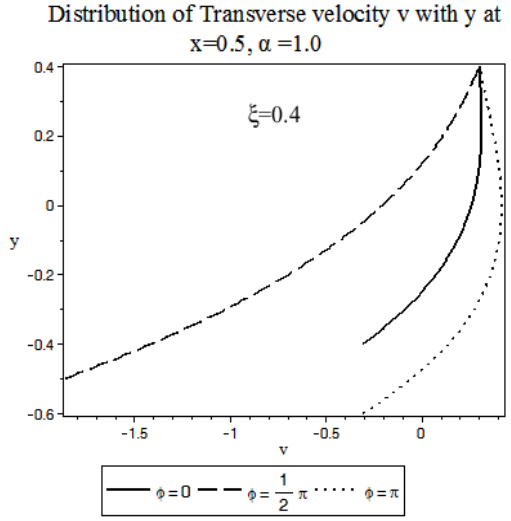




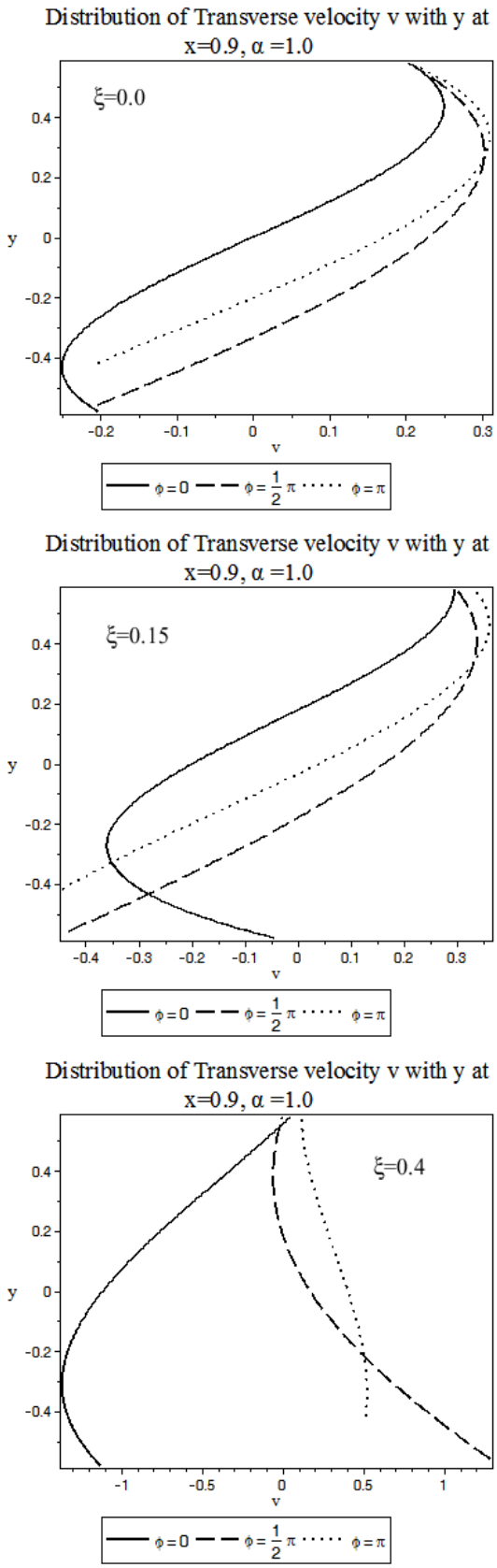
Figures 2(a)- 2(c) Distribution of Transverse velocity v with y at x=0.1, α=1.0



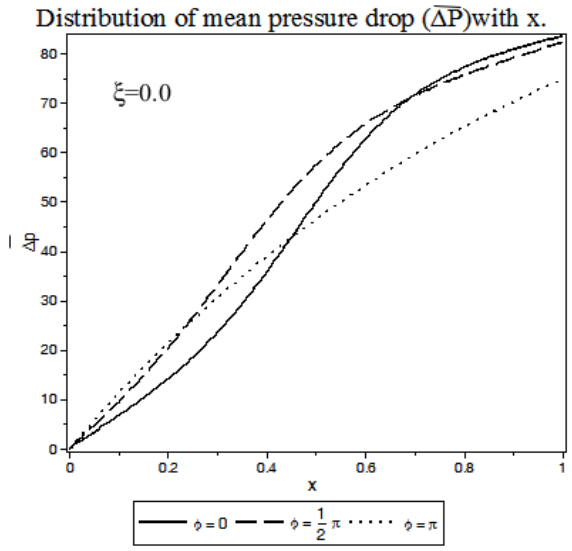


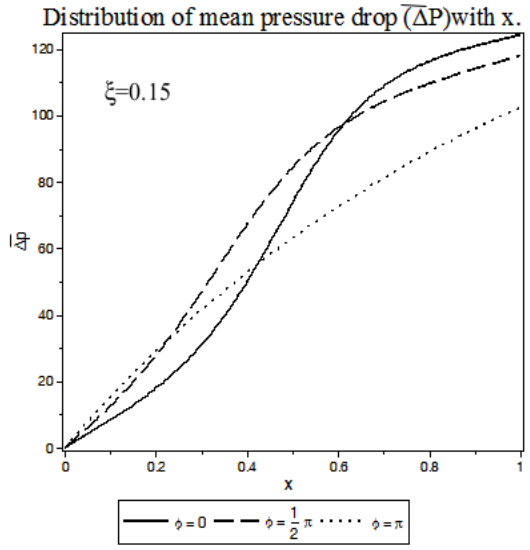


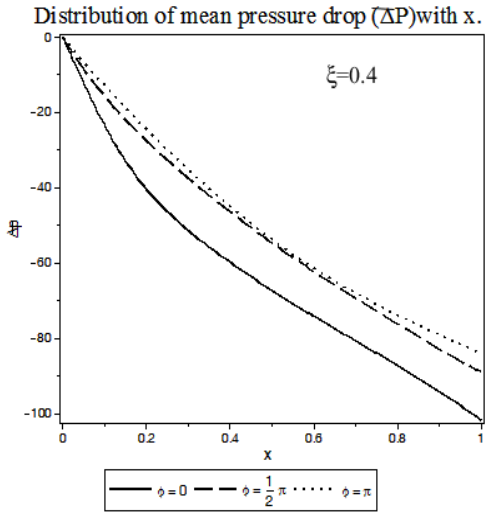
Figures 3(a)- 3(c) Distribution of Transverse velocity v with y at x=0.5, α=1.0



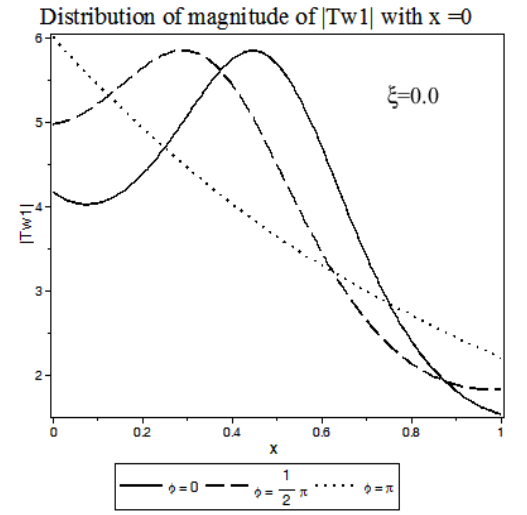
Figures 4(a)- 4(c) Distribution of Transverse velocity v with y at x=0.9, α=1.0

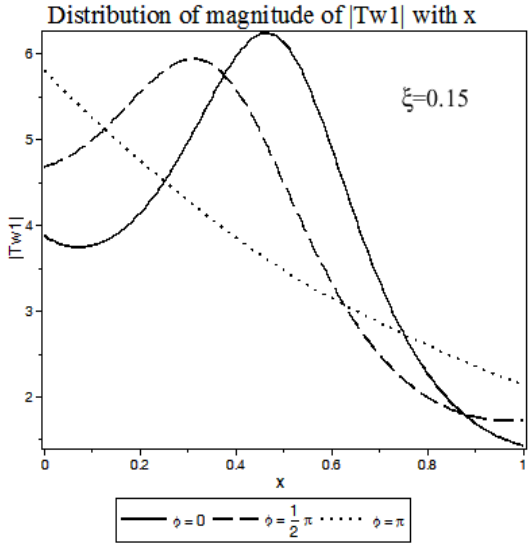


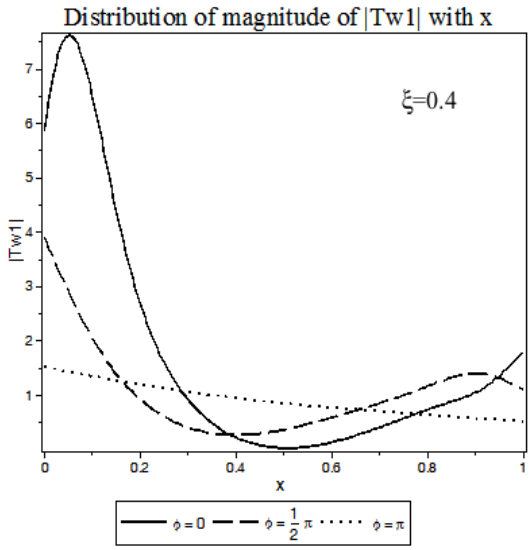




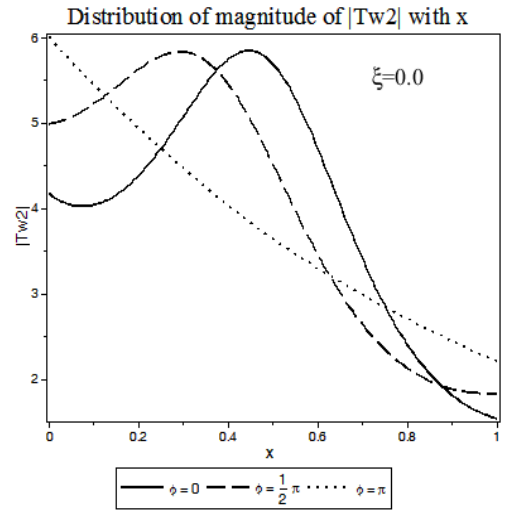
Figures 5(a)- 5(c) Distribution of Mean Pressure Drop with x

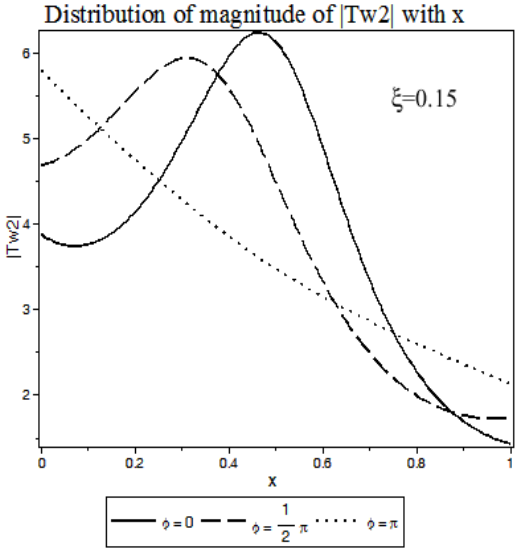


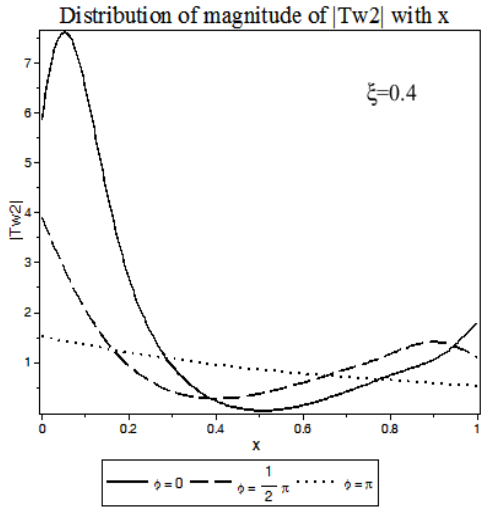




Figures 6(a)- 6(c) Distribution of Magnitude |$\mathcal{T}$w1| of with x







Figures 7(a)-7(c) Distribution of Magnitude | Tw2| of with x

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LABORATORY INVESTIGATION OF CEMENT PERMEABILITY BY USING DIFFERENT CHEMICALS

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ABSTRACT

Cement integrity is the key factor for thelong-term and future prospecting of the oil well having low permeability and decreasing its transitional time. Ultimately it provides a lending sheath to the well casing for future production preventing the collapse of formation as well as serve as a barrier for fluid movement between permeable zones. Permeability development within the cement increasesthe transitional time which results in loss of integrity and filtration may reduce the efficiency of cement leading to unsympathetic economic impact. Therefore determination of cement permeability by OFITE 120-87 has been considered useful to mitigate the wellbore problems associated with poor cementing.

The objective of present study is to conduct an experimental investigation of the cement permeability by using the cement permeameter (OFITE 120-87) at ambient conditions. The permeameter being used in this study is designed to determine the permeability of cement core specimen 1" X 1". The core specimen is placed into the core sleeve and then placed into the test cell known as "modified hassle ".The nitrogen gas is passed through the core specimen. The flow rate across the sample is recorded by a calibrated flow meter. The viscosity of flowing gas is 0.1756 cp at 25^0C.The variables from the study are integrated into Darcy law to calculate sample's permeability.

Keywords: Class G cement, cement permeameter, chemical additives and distilled water

1. INTRODUCTION

The foremost function of primary cementing is to achieve zonal isolation in order to prevent the fluid migration and ensure long-term cement integrity during the lifetime of the well. Current advanced drilling and cementing technologies enable the production of oil and gas in more complex challenging conditions such as deep wells and unconventional wells either onshore or offshore. Effective primary cementing would include a good casing-cement bond, cement-formation bond and ability of cement to prevent flow through it. The properties of the cement slurry and its behavior depend on the components and additives of the cement slurry design.
The cement permeability is also a key parameter in ensuring the durability of well throughout the production lifetime. Cement must have an impermeable matrix in order to provide zonal isolation

High cement permeability may lead to secondary cementing operation requiring additional expense. In thecase of severe conditions, welldamage can occur as well. These cement properties depend on various factors such as water to cement ratio, curing time, confining pressure and temperature and additives used to strengthen the cement.

The permeability of cement to gas is normally greater than the liquid permeability. The value of cement permeability without any additives is greater than 0.1md. The cement class G and H samples with various densities are aged under high-temperature conditions. During experimental work low permeability value was observed initially. However, the cement permeability was increased to 10 mdsover time. (Nelson, 1990)

Longer transitional time for cement slurry may become a cause of gas leakage or gas migration due to certain slurry performance. Gas migration can be prevented by speeding up the slurry from theliquid phase to thesolid phase by using thehighly efficient slurry to develop early age compressive strength.

Especially in the high-pressure gas wells, it is essential to control the flow of gas through the cement. In thecase of high cement permeability, the fluids may seep into the shallow portion of the formation near to the surface which may cause anincrease in pressure of shallow portion which then resultsin blowouts, weaker zonal isolation, and loss of reserves(Nelson, 1990).

Various laboratory tests could be carried out by using different additives at different concentrations to determine the cement permeability through cement permeameter. In this study,the cement, permeameter equipment is used to investigate the permeability by using Class G oil well cement with different proportion of additives and water to cement ratio at ambient conditions. This analysis will help in thebetter selection of cement slurry with anaccurate ratio of additives and water suitable for downhole conditions.

2. Literature Review:

Ozyurtkan, Altun, Mihcakan, & Serpen(2013)studied an experimental investigation for the prevention of permeability development within and around the set cement at ambient conditions by using the natural magnesium complex with carbonate (ARI) as a cement additive. Gas permeability measurements were conducted on 7” samples of 19 different compositions cured for a period of 1, 7 and 28days. Slurry was prepared using class G cement with 2% of ARI, 0.4% of viscosity control (CFR3) and 0.7% of water loss control (HALAD-9) additives by weight of cement, respectively. ARI additive was added to cement slurry with a ratio of 3% and 5%BWOC. It was revealed from the study that permeability of cement sample were decreased with addition of 3% of ARI BWOC and completely eliminated with the addition of 5% of ARI BWOC for all long aging time periods.

Roshan & Asef(2010)investigated the effect of carboxymethylcellulose(CMC) containing other additives on oil well cement in the Iran field focus to tectonically induce horizontally in-situ stress. On the basis of six months tests, the primary impact of additive carboxymethylcellulose CMC was observed on oil well cement. Temperature, density and Pressure of all tests were measured at 125^{o}C, 5200psi and 117 Lbm/ft^{3} respectively. The cement permeability was measured at 100psi and 20 ^{o}C after 24hours. It was found that permeability decreases from nearly 0.3md to less the 0.1md by addition of 0.4% of CMC. Furthermore,researchers also measured the early high compressive strength of cement at different ranges of proportions of CMC and friction reducer. It was observed

that the compressive strength increased by 37% at 0.2% CMC and 0.5% FR. It was concluded that extra CMC will remain undissolved and will have a negative impact on cement strength.

The flow of gas through cement sheath should be controlled, especially in high pressurized gas wells. If the cement is permeable enough, the fluids may percolate up to shallow portion of the formation around the well and/or to the surface. Such situations may cause an increase in the pressure of a shallow portion of the well, blowouts, weaker zonal isolations and production losses. (Nelson, 1990)

Vazquez, Blanco, & Colina(2005)evaluated the flow potential factor of three wells in Santa Barbara and San Joaquin fields located in Eastern Venezuela for optimum cement slurry design that prevents the industrial accidents and assuring the well life. The cement slurry formulation of three wells was evaluated. Results showed no gas migration for well 1, well 2 and well 3, in agreement with field observation. It was concluded that the slurry transition time must be based on the well FPF values. It is important to measure the FPF for each well for thelongterm integrity.

(Karakosta et al., 2015) presented a comprehensive laboratory assessment of the properties of two different non-foamed cement slurries such as fluid loss, thickening time and strength. He prepared two different slurries using class G cement with 43.8% and 31.3% of water BWOC according to API procedures. It was revealed from the study that NMR and ultrasonic measurement provide a comprehensive methodology for predicting the hydration properties of cement slurries with various additives at borehole conditions. Furthermore, it was found that addition of micronized silica increases the hydration rate significantly due to the effect of addition.

3. EXPERIMENTAL STUDY

3.1 Preparation of cement slurry and specimen

The cement slurry prepared according to the API recommended practice 10B for oil well cement. The procedure described below is recommended for laboratory preparation of slurries that require no special mixing conditions.

Step-IThe amount of class G cement and additives (barite, bentonite and caustic soda) with different proportions was weighted by electronic balance.

Step-II Class G cement and additives with different ratios was thoroughly and uniformly mixed prior to adding distilled water.

Step-III The cement and additives were added to the distilled water in a slurry blender and mixed continuously at 12000 rpm for 50 seconds. The temperature of dry cement and mix water was maintained at 20 ^{o}C -23^{o}C.

Step-IV The density of cement slurry was measured by mud balance and reported to be 15ppg (Pounds Per Gallon).

Step-V Slurry was prepared and then poured into a clean brass mold of 1” X 1” inch in length and diameter which had been placed on a flat plate and sealed. Then theslurry was puddled many times with stirring rod and leveled with a spatula. A top plate was carefully placed on the mold, so as not to trap air bubbles in the sample. See below figure.

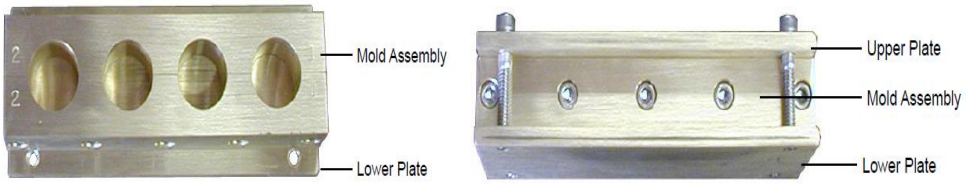

Fig 1: Four Gang Brass mold of 1" X 1" in length and diameter.

Step-VI Sufficient settling time was provided to the cement specimen to harden the cement.

Step-VII Cement specimens were then cured for 24 hours and 48 hours after removing them from the mold.

The cement slurries were prepared at 12ppg and 15ppg by using different proportions of bentonite, barite and water to cement ratio. The composition of cement sample with different percentage of bentonite and barite are given below.

Slurry-I contained 1% and 1.5%of barite BWOC with 15ppg density

Slurry-II contained 1% and 1.5% of bentonite BWOC with 12ppg density

Above samples were then cured for 24 and 48 hours in a water bath maintained at 27^0C. The permeability was then measured through cement permeameter.

Fig 2: Cement specimens with different proportions of chemicals prepared in Laboratory

3.2 Experimental procedure

The cement permeameter OFITE-120 is designed to measure the permeability of cement specimen of 1'' x 1'' in diameter and length as shown in the figure 3. A cement specimen is placed into core sleeve, which is then inserted into the "Modified Hassler" style test cell. The nitrogen at constant flow rate is passed through the cement and differential pressure across the cement is measured. The flow rate is measured with calibrated flow meters. The viscosity of nitrogen is 0.01756 cp. These variables are integrated into Darcy's law to calculate cement sample permeability.

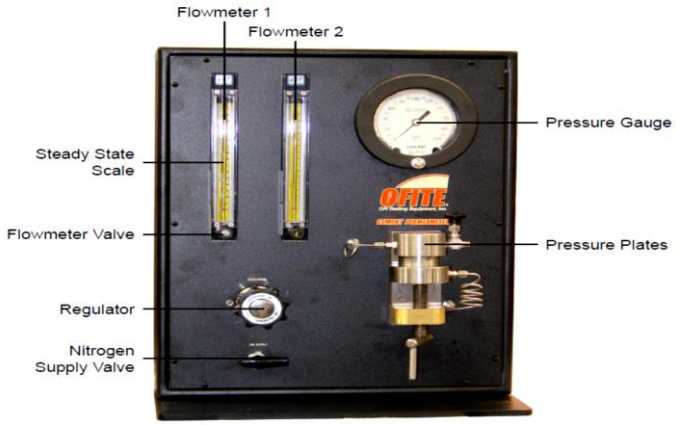

Fig 3: Cement Permeameter (OFITE Testing Equipment Inc.)

The Modified Hassler test cell accommodates the cement sample of 1'' length and 1''diameter. All Hassler components are fabricated from stainless steel. The flowmaters are used for low and high range flow-metering. Flow meter 2 is much more sensitive than Flow meter 1. If Flow meter1 does not register any appreciable flow rate at 180 PSI (1,249 kPa) then Flow meter 2 is used to take the readings. The nitrogen gas is supplied through the nitrogen supply valve by turning pressure regulator clockwise. Inlet pressure of nitrogen can be measured by the pressure gauge.

Permeability is calculated via Darcy's Law, which is stated mathematically

$$K = \frac{2000 P_o Q \mu L}{A(P_1^2 - P_o^2)}$$

Where *K* = Permeability, md

Po = Outlet Pressure, psig

Pi = Inlet pressure, psi

Q = Flow rate, cc/sec

μ = Viscosity, cp

L = Specimen Length, cm

A = Cross Sectional Area, cm^2

The cement specimen was placed into a rubber holder and which was then placed in to a rubber holder in the sleeve. Then the bottom plate was screwed upwards and tightened to ensure a good seal between the specimen and rubber holder as shown in the figure. The nitrogen gas was then supplied to the cement through the nitrogen supply valve. The valve of flowmeter 1 opened until the steady state scale reading on the flow meters registers 10. We record the inlet pressure (P1) from the pressure gauge. This procedure was repeated by opening the regulator and recording five

readings of inlet pressure at different intervals of each sample. The obtained values of flow meter and pressure were the substituted in the Darcy's equation to determine the permeability of each specimen.

Fig 4: Specimen holder, sleeve and test cell of Cement Permeameter OFITE-120

3.3 Results and Discussion

The gas permeability test results of the cement specimen with different proportions of additives and water to cement ratio areevaluatedand presented below.

The additive barite was added to the cement slurry with a ratio of 1%, and 1.5% BWOC. The gas permeability tests were performed after thecuring period of 24 hours and 48 hours. The results obtained from these experiments are summarized in Table 1.

Amount of barite % BWOC			Permeability , md	
			Curing periods, hours	
			24	48
1			0.60	0.25
1.5	0.48	0.11		

Table 1: Permeability values cement specimen with various % of Barite.

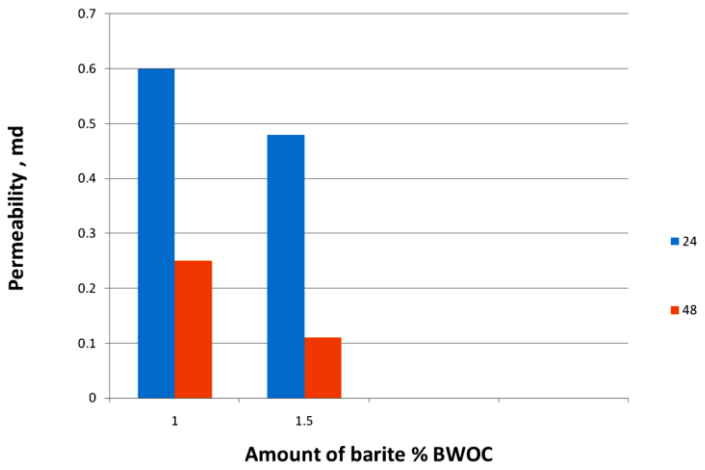

Fig 4: Graph - Permeability values cement specimen with various % of Barite.

The additive bentonite was added to the cement slurry with a ratio of 1% and 1.5% BWOC. The gas permeability tests were performed after the curing period of 24 hours and 48 hours. The results obtained from these experiments are summarized in Table 2.

Amount of Bentonite % BWOC	Permeability , md	
	Curing periods, hours	
	24	48
1	0.85	0.40
1.5	1.2	0.6

Table 2: Permeability values cement specimen with various % of Bentonite

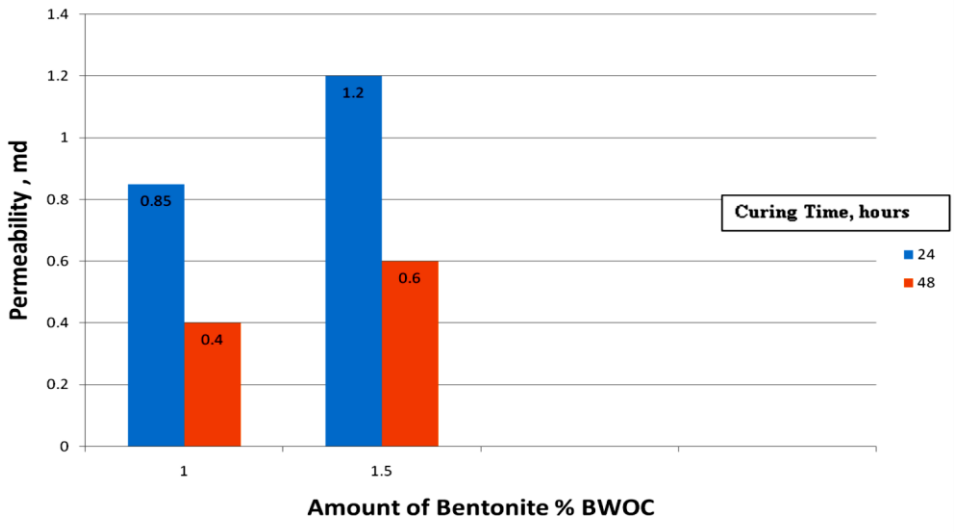

Fig5: Permeability values cement specimen with various % of Bentonite

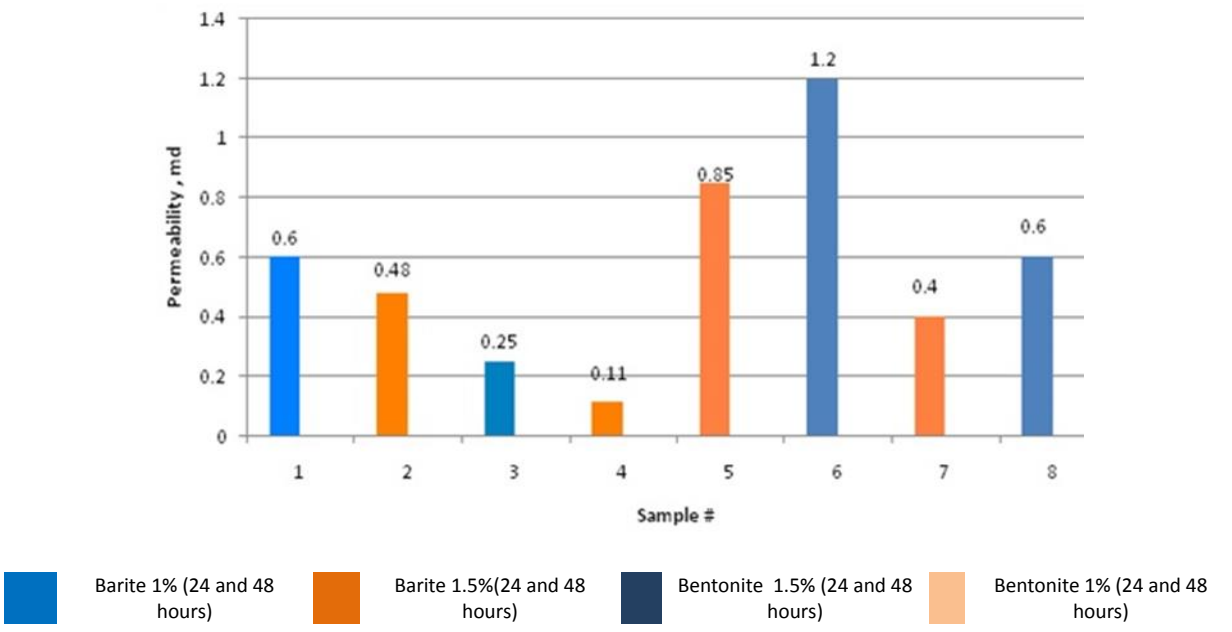

Fig 6: Permeability values of various cement specimens with different % of Barite and Bentonite.

CONCLUSION

The light cement slurry with 12ppg was prepared by using bentonite. It is noted that permeability can be decreased with increasing curing time to 48 hrs due to the increase in compressive strength.

The density of 15ppg slurry was prepared by using barite concentrations. It is noted that permeability was reduced by increasing curing time and it became more stable reducing filtration.

NOMENCLATURE

BWOC= by weight on cement
md= Millidarcy
cp= Centipoise
cm= Centimeter
cc/sec =Cubic centimeter per scond
atm = Atmospheric pressure
ppg =Pounds per gallon

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